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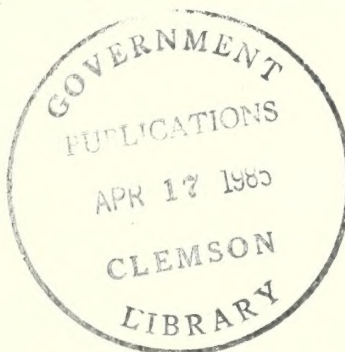
General Technical
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Programs for Computer Simulation of a Crosscut-First Furniture Rough Mill

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The Author

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Abstract

Computer programs for simulating a crosscut-first furniture rough mill were developed to include all operations from the lumber breakdown hoist through the crosscut saws to the final machining-to-width on rip saws. The programs allow the user to measure the effects of changes in the factors affecting production costs and to determine total processing costs for individual parts leaving the furniture rough mill. A combined continuous/discrete FORTRAN-based simulation language (GASP IV) was used.

Note

The computer program described in this publication is available on request with the understanding that the U.S. Department of Agriculture cannot assure its accuracy, completeness, reliability, or suitability for any other purpose than that reported. The recipient may not assert any proprietary rights thereto nor represent it to anyone as other than a Government-produced computer program. For cost information, please write:

Northeastern Forest Experiment Station, Forestry Sciences Laboratory, P.O. Box 152, Princeton, West Virginia 24740.

Introduction

In any processing of wood, production costs on an individual-part basis are needed to accurately compare various types of rough-mill configurations. Analyzing the production costs in an existing crosscut-first furniture rough mill can be done by using a computer simulation technique (Anderson 1983). Two computer programs, MILLSIM 1 and MILLSIM 2, were developed at the Forestry Sciences Laboratory as simulation models of an existing rough mill to include all operations from the lumber breakdown hoist through the crosscut saws to the final machining-to-width on rip saws.

The purpose of this paper is to present the computer models and documentation for an existing crosscut-first furniture rough mill. These models allow the user to measure the effects of changes in the factors affecting production costs and to determine total processing costs for individual parts leaving the furniture rough mill.

The System Studied

We simulated the production processes of an existing rough mill. The processes are typical of those encountered in any well-run conventional crosscut-first rough mill. The choice of simulating an existing rough mill has several advantages over simulating a hypothetical rough mill. First, production figures from the existing mill provide benchmarks for evaluating the simulated production performance. Second, production parameters are well established in an existing mill. And third, cooperation of mill management assures that production parameters can be determined with greater accuracy than would otherwise be possible.

The crosscut-first furniture rough mill is a sequence of operations that begins with the input of graded, kiln-dried hardwood lumber and ends with the output of dimensioned parts of specific lengths and widths. Operations represented in the model are outlined in Figure 1.

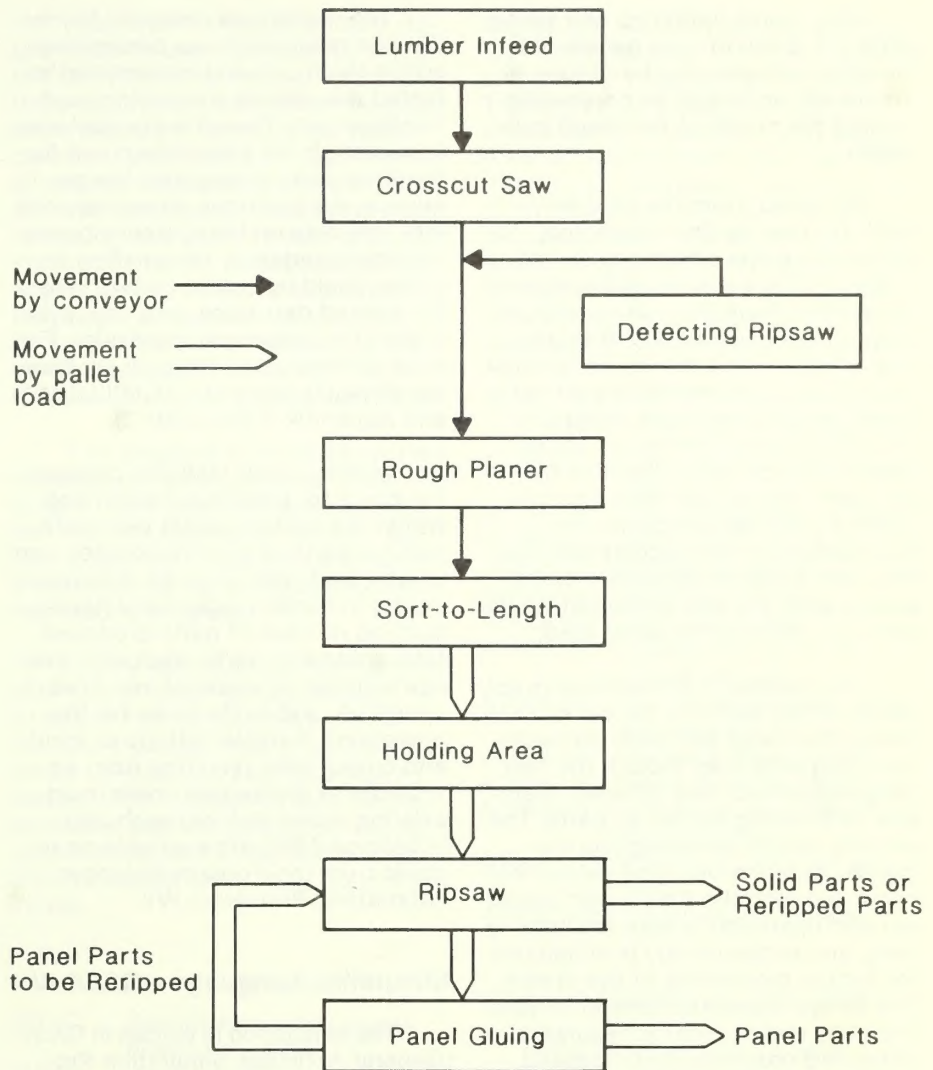


Figure 1.—Sequence of operations in rough mill.

Lumber enters the rough mill on a lumber breakdown hoist that unstacks boards onto a cross conveyor. After boards are removed from the cross conveyor at a crosscut saw, they are processed into cut-to-length, random-width parts. These parts drop onto a conveyor that takes them past a defect ripsaw, where excessive cup or other defects are removed, to a planer that skip planes the boards on both sides to a standard thickness. From the planer, parts move up a conveyor to a sort station where they

are sorted by length onto pallets and moved to a holding area. As needed, parts are moved from the holding area to a rip saw for one of four processing operations:

- rip to remove defects followed by rip to specified width
- rip to remove defects followed by rip to produce glue-line edge
- panel matching and sizing
- rip glued-up panels back to specified width

Model

After panel matching and sizing, parts are glued up into panels that are either returned to the rip saw or are moved on to further processing beyond the scope of the rough mill model.

As noted, from the lumber infeed to the sorting operation, the material is passed from one operation to the next by a system of fixed-speed conveyors. From the sort operation through the machining-to-final part size, all material is conveyed by pallet load. Each pallet contains parts of a single length and grade. Program MILLSIM 1 simulates those operations where parts are handled by conveyor. The output from this program is used as part of the input information for the second program, MILLSIM 2, which simulates those events after the sort operation where parts are handled by pallet load.

The method of conveyance is not the deciding factor in the decision to model the rough mill with two separate programs even though the two programs reflect two different methods of handling lumber or parts. The primary reason for using two programs centers around the delays that occur between the time a part leaves the sort operation, enters the holding area, and subsequently is scheduled for further processing at the rip saw. The delays depend on several factors, including overall plant schedules, size of cutting orders being processed, and the amount of storage space available in the holding area. These delays are neither consistent nor predictable with any great accuracy. Therefore, if we model all of the processes on one side of the holding area separately from those on the other side, we are assured that the timing between each process is consistent with the actual mill operation. Also, the cost of handling parts can be divided between the processes before and after the holding operation.

The model was designed to identify and measure those parameters within the rough-mill system that affected the cost of processing each furniture part. The ultimate goal was to establish the processing cost for furniture parts throughout the sequence of operations. Input required includes data on the system's operating characteristics, information on lumber yield by grade, cutting orders for desired part sizes, and cost information for lumber and processing. Formats of input data for each program are shown in Appendix IV (MILLSIM 1) and Appendix V (MILLSIM 2).

Model output includes processing costs for individual operations within the system, costs per board foot for parts of specific lengths and widths, and yield of parts. Additional output includes productivity figures such as number of parts produced, total volume of parts produced, average volumes of material lost at each operation, and cycle times for the operations. Sample listings of input and output data resulting from an analysis of production costs in an existing crosscut-first rough mill (Anderson 1983) are available on request from the Forestry Sciences Laboratory, Princeton, WV.

Simulation Language—GASP IV

The simulation is written in GASP (General Activities Simulation Program) IV: A combined continuous/discrete FORTRAN-based simulation language (Pritsker 1977). The programs include a main source program and processing-event subroutines that describe a system's dynamic behavior. These programs use variables, functions, and subroutines supplied by the GASP IV simulation language (listed in Appendix I) as well as user-defined variables (listed in Appendices II and III). In addition, the simulation model contains: lists and matrices that store information, an executive routine that directs the flow of infor-

mation and control within the model, and support routines. These form an operating computer program that reflects the simulated system.

Model Assumptions—MILLSIM 1

The following assumptions are made about the system's behavior in program MILLSIM 1, which simulates operations from the board infeed through the sort operation:

1. Board input is generated based on distributions of board sizes for different grades of lumber. Board input is scheduled to ensure that the cross conveyor carrying boards to the crosscut saws is between 75 and 100 percent filled. This ensures that no delays occur between the end of crosscutting one board and the availability of a new board on the cross conveyor. For example, boards are placed on the cross conveyor until the sum of the individual board widths equals the overall length of the cross conveyor. At this point, the cross conveyor is 100 percent filled, and individual boards can be pulled off the conveyor for processing at the crosscut saw. As each board is removed, the sum of remaining board widths is reduced. This process continues until the sum of board widths falls below 75 percent of the cross conveyor's length. At this time, additional boards are placed on the cross conveyor until the sum of board widths again equals the overall length of the cross conveyor.

2. The defecting rip saw does not operate on every part that passes on the conveyor to the rough planer. Only a specified percentage of the total number of parts on the conveyor are ripped to remove either defects or excess cup. After these parts are ripped, they are returned automatically to the conveyor where they, along with all parts that bypass the rip saw operation, are conveyed directly through the planer operation.

3. The sort operation is the control point for introducing a new length or deleting a length on the current cutting bill. As parts are removed from the conveyor at the sort operation, the number and quantity of parts in each length class are tallied. When the required quantity of a particular length part is produced, a change in the current cutting bill is made. The length for the part that has been produced in the required quantity is taken off the current cutting bill, and a new part length is added to the cutting bill.

Model Assumptions—MILLSIM 2

Additional assumptions about the system's behavior in program MILLSIM 2, which simulates operations from the holding area through final machining to size, include:

1. In scheduling a specific part for processing at a rip saw station, the model continues processing at the rip saw station until the total input volume for that part has been exhausted. In the actual mill, material for a specific part arrives at the rip saw on a pallet. Each rip saw processes all of the material on a pallet before starting on a new pallet load of material. In the model, the rip saw continues to receive pallet loads for the same size part until the total input volume for that part has been processed.

2. A rip saw becomes idle when a specific part's cutting requirement is completed. Then, either a new part is scheduled for ripping or, if none remain, the rip saw is scheduled to process a part size that another rip saw may also be currently working on. In this way, the time a rip saw is idle is held to a minimum. Also, large requirements for a specific part size are handled quickly by utilizing more than one rip saw to meet the requirement.

3. Parts that have been ripped to produce a glue-line edge are scheduled to reach the gluing operation within the next 8-hour shift. This delay allows sufficient buildup of parts awaiting gluing so that the gluing operation is kept busy at all times.

Program Operation—MILLSIM 1

MILLSIM 1 includes a main program and 10 user subroutines written in FORTRAN. The main program has three functions: (1) establish the array dimensions for common variables called in GASP and user subroutines, (2) read in values for all of the variables associated with the rough mill's operating characteristics, and (3) call subroutine GASP. Subroutine GASP is provided by GASP-IV simulation language. It supplies the controls necessary for the simulation to advance from one processing step to the next in a time-ordered sequence.

This program is currently written to operate in a batch mode. Thus, the program and data are combined in one file and submitted for each run. The output from each run is stored in a separate file for subsequent use in the second program.

The 10 user subroutines perform activities in three general areas: (1) define the starting state of the mill and the sequence of processing steps, (2) simulate each processing step, and (3) summarize and file the statistics that are generated during each simulation. These subroutines with a description of their functions follow:

<i>Sub-routine</i>	<i>Function</i>
INTLC	Establishes initial conditions in the mill
EVNTS	Identifies which operation is performed next
BREAK	Inputs new board dimensions
CUTOFF	Performs cutoff saw operation
DEFECT	Performs defecting rip saw operation
PLANE	Performs rough planing operation
PSORT	Performs sort operation
PSAVE	Collects statistics on part characteristics
OTPUT	Controls printing and storage of results
DISCR	Generates discrete number distribution

As the simulation moves from one processing step to the next, information about the parts currently in the system must be alternately

stored and transferred from one subroutine to the next. This is done using a system of files defined by GASP. These files, or storage arrays, are contained in the arrays NSET/QSET. A set of values called attributes identify the part information that is stored or retrieved from the files. The values are contained in the vector identified as GASP variable ATRIB. Subscripts for the vector elements identify specific attributes or part information as shown in the following tabulation:

<i>Subscript number</i>	<i>Part attribute identified in program MILLSIM 1</i>
ATRIB (1)	Time event or processing step occurs
ATRIB (2)	Type of processing step
ATRIB (3)	Time board enters system
ATRIB (4)	Length, in inches
ATRIB (5)	Width, in inches
ATRIB (6)	Cost, in dollars
ATRIB (7)	Cost added by current operation
ATRIB (8)	Volume of material lost in operation
ATRIB (9)	Crosscut saw number
ATRIB (10)	Level of cross conveyor
ATRIB (11)	Volume, board feet, in original board
ATRIB (12)	Volume, board feet, of part
ATRIB (13)	Thickness, in inches

Program Operation—MILLSIM 2

MILLSIM 2 includes a main program and 14 user subroutines written in FORTRAN. The main program has essentially the same functions as the previously described main program with one addition, MILLSIM 2 takes the physical and cost characteristics of parts coming from the sort operation and uses them to simulate the conversion to parts of specific length, width, and grade. Thus, one additional function is performed by the main program in MILLSIM 2 to read in values' output from MILLSIM 1 that describe the physical and cost characteristics of parts coming from the sort operation. This program is also a batch-mode program. The program and data from the preceding program are combined in one file and submitted for each run. After reading in the part information, the main program transfers control of the sim-

ulation to subroutine GASP. This subroutine again controls the sequence of processing steps simulated by the 14 user subroutines. These subroutines with a description of their functions follow:

<i>Sub-routine</i>	<i>Function</i>
INTLC	Establishes initial conditions in the mill
EVNTS	Identifies which operation is performed next
INFEED	Controls input of new part length
RIPARR	Schedules next part arrival at rip saw
RIPDEP	Schedules next part departure at rip saw
GLUARR	Schedules next part arrival at gluing operation
GLUDEP	Schedules next part departure at gluing operation
INTPRT	Controls intermediate printing of results
FPSAVE	Summarizes part costs
OTPUT	Controls printing of results
RIPTIM	Calculates time required for rip operation
CNDRM	Calculates normal distribution for costs
WNORM	Calculates normal distribution for widths
RQUEUE	Calculates mean, standard deviation, minimum and maximum values for part characteristics between the glue-line edge rip and the panel matching/sizing rip operations

This program also uses the vector identified as GASP variable ATRIB to identify the part information as it is stored or retrieved from files during the simulation. Subscripts for the vector elements again identify specific attributes or part information as shown in the following tabulation:

<i>Subscript number</i>	<i>Part attribute identified in program MILLSIM 2</i>
ATRIB (1)	Time event or processing step occurs
ATRIB (2)	Type of processing step
ATRIB (3)	Ripsaw number
ATRIB (4)	Length, in inches
ATRIB (5)	Width, in inches, of current part
ATRIB (6)	Width, in inches, of finished part
ATRIB (7)	Cost of current part
ATRIB (8)	Volume of material lost in operation
ATRIB (9)	Length class of panel
ATRIB (10)	Width, in inches, of panel
ATRIB (11)	Previous type of event

Summary

These programs were used to simulate the processing of a typical rough mill cutting order (Anderson 1983). Results of this simulation indicate that the programs realistically reflect the operation of an existing crosscut-first furniture rough mill. The programs, as listed in the Appendixes, can easily be modified, through changes in input variables and minor internal changes, to reflect the operating characteristics of any conventional crosscut-first rough mill.

Literature Cited

- Anderson, R. Bruce. **Furniture rough mill costs evaluated by computer simulation.** Res. Pap. NE-518. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1983. 11 p.
- Pritsker, A. Allen B. **The GASP IV user's manual.** 2d ed. West Lafayette, IN: Pritsker & Associates, Inc.; 1977. 100 p.

Appendix I—GASP Program Variables

The following GASP variables (V), functions (F), and subroutines (S) may be found in both programs. A description of their application may be found in the GASP IV User's Manual (Pritsker 1977).

ATTRIB (V)	PPARM (V)
COLCT (S)	QSET (V)
COPY (S)	RMOVE (S)
DRAND (S)	RNORM (F)
FILEM (S)	SET (S)
MFA (V)	SSOBV (V)
MFE (V)	SUMQ (F)
MLE (V)	TIMST (S)
MMAXQ (V)	TTBEG (V)
MSTOP (V)	TTFIN (V)
NNQ (V)	TTNEX (V)
NSET (V)	UNFRM (F)
NSUCR (F)	

Appendix II—Variables—MILLSIM 1

Variables in program MILLSIM 1.

ABBDFT:	Board foot required to satisfy an order for a specific part length in MILLSIM 2.
AVG:	Average value for attribute defined by PXS in subroutine PSORT.
BC:	Calculated cost of each board entering rough mill.
BDFTP:	Array containing sum of board feet for each part length.
BFT:	Calculated board-foot volume of each board entering rough mill.
BFTO:	Array containing calculated board-foot overrun for each part length.
BOTCH:	Current total width of boards on bottom infeed cross conveyor.
BRDOBS:	Current number of parts having arrived at the sort operation.
CD:	Array containing mean, standard deviation, and minimum and maximum value of part cost for each part length.
CHOIST:	Calculated cost per board attributed to breakdown hoist labor.
CLABOR:	Array containing labor costs per hour by type of operation and day or night shift.
COMPLT:	Calculated percent of required board-foot input that has been processed.
COST:	Material cost per board foot of lumber input—depends on grade of lumber input.
CP:	Array containing total cost of parts by part length.
CPAVG:	Average cost per part for each part length calculated by dividing total cost CP by total board feet BDFTP.
CPROB:	Array containing cumulative distribution function for number of parts cut.

CPTAVG:	Average cost per part for all part lengths.
CRAT:	Operating rate for cutoff saw in board feet per minute.
CRRAT:	Array containing times expected between cutoff saw and defecting rip saw.
CRTIME:	Expected time to perform cutoff operation for each part.
CTIME:	Expected time to perform all cutoff operations on a given board
CV:	Calculated coefficient of variation for a specified attribute.
CWASTE:	Calculated trim loss on cutoff saw operation expressed as board feet.
CWCOST:	Calculated cost of trim loss at cutoff saw.
FPWD:	Array of panel widths for part lengths processed in MILLSIM 1.
FPWDC:	Array of panel widths per part lengths processed in MILLSIM 2.
FTHIC:	Specified maximum thickness of part leaving rough planing operation.
FWID:	Array of final part widths for part lengths processed in MILLSIM 1.
FWIDC:	Array of final part widths for part lengths processed in MILLSIM 2.
IBUSY:	Array of flags to determine if cutoff saw is busy or idle.
IC:	Number of cuts per board at the cutoff saw generated using a uniform discrete distribution.
IFI:	Integer counter used in determining entry of new part length into cutting bill.
IGRADE:	Array of part grade by length of part.
IT:	Integer counter used in determining departure of part length from cutting bill.
IJ:	Integer counter specifying a specific part length within several operations.
ILENC:	Total number of length-width combinations input to the data storage for MILLSIM 2.
IM1:	Integer counter used to sum individual probabilities into a cumulative distribution.
INBRD:	Number of boards input onto cross conveyor following breakdown hoist.
INBRD1:	Number of boards input on top chain of cross conveyor.
INBRD2:	Number of boards input on bottom chain of cross conveyor.
INDX:	Counter used in retrieval of board data from storage file QSET.
IPPAR1:	Subscript for array of length parameters for specific board grade.
IPPAR2:	Subscript for array of width parameters for specific board grade.
IPRIOR:	Assigned priority for part lengths entering the cutting bill.
ISAV:	Integer subscript used to specify attribute on which statistics are being collected.
ISAW:	Integer subscript defining the crosscut saw that the operation is being performed on.

ISCHED:	Next part length considered for entry into the active cutting bill.	PSCHED:	Array containing part length, in inches, and volume required, in board feet, for all input lengths in the cutting order.
ISHIFT:	Current shift of operations, either first- or second-shift labor rates applied.	PSRAT:	Expected time between planer and sort operations.
IT:	Level of cross conveyor, top or bottom.	PWCST:	Cost associated with trim waste in planer operation.
ITHK:	Subscript defining array location of thickness parameters.	PXS:	Value of attribute on which statistics are being collected.
ITIJ:	Saw number of current operation.	RATR:	Operating rate for defecting rip saw in lineal feet/minute.
IX:	Part length resulting from cutoff saw operation, specified as part number.	RBDL:	Remaining board length after part length and/or trim loss have been subtracted.
JJ:	Subscript for attribute on which statistics are being collected.	REPLA:	Part length, in inches, leaving active cutting bill.
JSJ:	Same as JJ.	REPLB:	Part length, in inches, entering active cutting bill.
KLEFT:	Number of part lengths left in active cutting bill.	RN:	Random number, between 0.00 and 1.00.
KSCHED:	Initial number of part lengths in the cutting bill actively being cut.	RPRAT:	Expected time between defecting rip saw and rough planer.
KSTART:	Current shift of operations in which idle crosscut saw is restarted.	RQBFT:	Total board-foot input required as calculated by summing requirements for each part length.
LABL1:	Alpha-numeric label used in printing results.	RTIME:	Expected time to complete defect rip saw operation for a specified part length.
LABL2:	Alpha-numeric label used in printing results.	RWCOST:	Cost of material lost in processing at defecting rip saw operation.
LBL1:	Alpha-numeric label used in printing results.	START:	Time delay used in restarting cutoff saws that were idle.
LBL2:	Alpha-numeric label used in printing results.	STD:	Computed standard deviation for specified attribute.
LBL3:	Alpha-numeric label used in printing results.	STDM:	Computed standard deviation of the mean for specified attribute.
LBL4:	Alpha-numeric label used in printing results.	SUMBFT:	Calculated sum of board-foot volume actually input to rough mill.
LENC:	Array of part lengths to be processed in MILLSIM 2.	TBFT:	Total board-foot volume of lumber input to the rough mill during the simulation.
LEVEL:	Level of cross conveyor, top or bottom, from which board was taken.	TBF2:	Board-foot volume remaining on cross conveyor at end of simulation.
MBDFTP:	Flag to determine if part length has entered the active cutting bill.	TBREAK:	Expected time interval between successive operations of lumber input to cross conveyor.
NCRDR:	Unit number of input device.	TCINC:	Expected time for crosscut saw operation on a specific part.
NCUT:	Number of cuts per board at the cutoff saw associated with a specific probability.	TEMPA:	Temporary variable used in longest to shortest ordering of lengths in current cutting bill.
NJ:	Counter used in selected printing of results.	TEMPP:	Same function as TEMPA.
NJBFT:	Specified grade of lumber input.	THICK:	Input variable specifying nominal thickness of lumber input.
NPART:	Generated number of parts to be produced from a given board.	TNOW:	Current time of simulation.
NPRNT:	Unit number of output device.	TOPCH:	Current total width of boards on top infeed cross conveyor.
NSBEG:	Constant used in storage of data for further processing by MILLSIM 2.	TPF1:	Board-foot volume of parts in system prior to sort operation at end of simulation.
NSCHED:	Total number of part lengths to be processed.	TPLNE:	Expected processing time for specific part length in rough planer operation.
NXN:	Number of parts of a specific length that passed through the sort operation.	TRANP:	Total time spent in processing from lumber infeed operation to sort operation.
PARTL:	Array of part lengths in active cutting bill, specified in inches.	TRIME:	Total length, in inches, of trim loss in processing at cutoff saw.
PBBDF:	Board-foot volume available to satisfy a specific part order in MILLSIM 2.		
PCUT:	Number of parts associated with a specific number of crosscuts per board.		
PLENCT:	Array defining percentage of output for a specific length part that will be used as input in MILLSIM 2.		
PLN:	Array of part lengths in active cutting bill, specified in inches.		
PRAT:	Operating rate for planer in lineal feet per minute.		
PRTCST:	Processing cost associated with given operation.		

Appendix III—Variables—MILLSIM 2

Variables in program MILLSIM 2.

TRIMI: Initial trim loss, in inches, from board processed at cutoff saw.

TWAS1: Volume of material lost in processing, expressed in board feet, at end of simulation.

VARAN: Computed variance for specified attribute.

WD: Array containing mean, standard deviation, minimum and maximum value of part width for each part length.

WMAX: Observed maximum value for specific attribute on which statistics were collected.

WMIN: Observed minimum value for specific attribute on which statistics were collected.

WN: Number of observations for a specific attribute on which statistics were collected.

WP: Array of total width of parts, in inches, for all part lengths processed.

WS: Array containing sum of observations for a specific attribute.

WSS: Array containing sum of squared observations for a specific attribute.

X: Random number, ranging in value from 0.00 to 1.00.

XBDFT: Volume, in board feet, of material lost.

XCBFT: Volume, in board feet, of part arriving at defecting rip saw operation.

XCCST: Current processing costs associated with part arriving at defecting rip saw operation.

XKSC: Number of parts in current active cutting bill expressed as a real number.

XLN: Part length to be cut from board.

XN: Same function as WN.

XNPART: Same function as NPART, expressed as a real number.

XPCT: Percentage of part width to be removed in defecting rip saw operation.

XRBFT: Volume, in board feet, of part arriving at rough plane operation.

XRCST: Current processing costs associated with part arriving at rough planing operation.

XRWD: Width of part, expressed in inches, of part after defecting rip saw operation.

XS: Same function as WS.

XSS: Same function as WSS.

XTBDFT: Sum of board-foot volume of parts leaving the sort operation.

XTCP: Sum of processing costs for parts leaving the sort operation.

XTHIC: Thickness, expressed in inches, of material lost in processing at rough planing operation.

XWD: Width of part, expressed in inches, lost during defecting rip saw operation.

YIELD: Calculated percentage of total volume of lumber input resulting in parts output.

ABFT: Array containing board-foot volume available for processing by specific part length.

ALEN: Array containing lengths of parts, in inches.

APWD: Array containing panel widths, in inches.

AWID: Array containing finished part width, in inches.

CBFT: Average cost per finished part.

CD: Array containing mean, standard deviation, and minimum and maximum value of part cost for each part length entering system.

HRBFT: Specified percentage of required board-foot volume, used as a control to add rip saws.

IBUSY: Array of flags to determine if rip saw is busy or idle.

ICHRG: Number of panels in current charge of gluing operation.

ICNT: Length class of part or panel in current operation.

IFLAG: Array of flags to determine next rip saw operation.

IGFLAG: Flag used to determine status of gluing operation.

IGRADE: Array of part grades by length of part.

II: Argument in RQUEUE subroutine used to determine whether summation of attributes by part length is complete.

IMATCH: Flag used to determine whether panel matching operation for specific part length is complete.

INDX: Variable determining number of observations stored in a specific array.

INPUTT: Length class of part or panel that is entering the current operation.

INRC: Previous type of event occurring prior to INFEED event.

INSAW: Number of rip saw referred to in current operation.

IREVNT: Type of rip event occurring—solid part sawing, panel matching, reripping panels, etc.

IRIP: Number of rip saw referred to in current operation.

IT: Length class of panel in current operation.

ITPCNT: Flag to prevent division by zero in summation routine in OPUT and INTPRT.

ITYPE: Same function as IT.

IX: Argument in subroutine EVNTS that determines which operation is performed next.

JEND: Flag used at end of simulation to control printing of results.

JEVNT: Time-event code defined by ATRIB (2).

JJ: Argument in RQUEUE that specifies length class of part.

JKEND:	Same function as JEND.	TBFT:	Total board-foot volume of each part size that has been completely processed.
JMATCH:	Flag used to determine whether panel matching has been scheduled for specific part length.	TCOST:	Total processing costs for each part size that has been completely processed.
JQEND:	Same function as JEND.	TDEP:	Expected time for complete processing of a part at a given operation.
K:	Argument in subroutine that specifies either length class or type of rip operation performed.	TNOW:	Current time of simulation.
KPCNT:	Flag used to determine whether all part lengths have finished rip saw operation.	V:	Calculated standardized normal deviate.
KPEND:	Flag used to control intermediate printing of results.	VCC:	Computed variance for cost of a specific part size.
KQEND:	Same function as KPEND.	VML:	Computed variance for material lost in processing a specific part size.
KRCNT:	Total number of part length-width combinations in simulation.	VWC:	Computed variance for width of part for a specific part size.
LCPAN:	Same function as ICNT.	WBFT:	Calculated board-foot volume lost in rip saw processing of individual part.
NCRDR:	Unit number of input device.	WD:	Array containing mean, standard deviation and minimum and maximum value of part width for each part length entering system.
NFICNT:	Same function as ICNT.	XCC:	Array containing sum of costs for all part lengths.
NGFLAG:	Counter specifying number of part lengths awaiting availability of gluing operation.	XMATCH:	Generated random number used to determine whether or not panel match operation is scheduled.
NHRS:	Number of hours between activation of intermediate print event.	XML:	Array containing sum of board-foot volume of material lost for all part lengths.
NPANC:	Number of finished-to-width parts that can be ripped from glued-up panels.	XNC:	Number of observations for a specific part length on which statistics were collected.
NPARC:	Number of finished-to-width solid parts that can be ripped from current part length.	XPC:	Processing cost for individual parts leaving the solid part ripping operation.
NPART:	Number of parts of a specific size that have completed processing.	XTRIM:	Quantity, in inches of width, of trim loss in ripping to produce glue-line edge operation.
NPCHRG:	Number of panels that are input to the gluing operation.	XWC:	Array containing sum of part widths for all part lengths.
NPRNT:	Unit number of the output device.	XXCC:	Array containing sum of squared part costs for all part lengths.
NRIPC:	Flag used to control summarization of output for specific part length.	XXML:	Array containing sum of squared volume of material lost for all part lengths.
NRIPQ:	Number of parts, by specific length, awaiting panel matching at the rip saw.	XXWC:	Array containing sum of squared widths for all part lengths.
NSBEG:	Beginning number for part size that enters the system first.	YBFT:	Calculated percent of total volume of part input resulting in part output.
NSCHED:	Total number of part sizes to be processed.	ZCC:	Array of mean, standard deviation, and minimum and maximum cost for all part lengths after processing.
NSEND:	Ending number for part size that enters the system last.	ZML:	Array of mean, standard deviation, and minimum and maximum volume of material lost for all part lengths after processing.
NXTRIP:	Variable used to define the previous type of operation and schedule the next operation.	ZWC:	Array of mean, standard deviation, and minimum and maximum width of part for all part lengths after processing.
PANCOS:	Processing costs for individual parts going into a panel matching operation.		
PANSUM:	Sum of widths of individual parts going into a panel matching operation.		
PANTYP:	Control variable in panel matching operation used in scheduling next operation.		
PARCOS:	Processing cost for individual parts leaving the panel ripping operation.		
RBFT:	Array of input board-foot volume required to satisfy cutting requirements for specific part size.		
RGCYCL:	Cycle time for gluing operation, specified in minutes.		
RLAYUP:	Time required for layup of panels in gluing operation, calculated in minutes.		
SUM:	Sum of 12 random numbers used in calculating a standardized normal deviate.		

Appendix IV—Input Instructions for MILLSIM 1

All data for MILLSIM 1 can be input using a standard 80-column, card-image format. Columns between 1 and 80 that are not specifically numbered in the following input formats contain no data and should be left blank.

Card 1

Columns

1-8	Nominal thickness of lumber input, in inches (THICK)
9-16	Operating rate for cutoff saw in board feet per minute (CRAT)
17-24	Operating rate for defecting rip saw (#1) in lineal feet per minute (RATR(1))
25-32	Operating rate for defecting rip saw (#2) in lineal feet per minute (RATR(2))
33-40	Operating rate for planer (#1) in lineal feet per minute (PRAT(1))
41-48	Operating rate for planer (#2) in lineal feet per minute (PRAT(2))

Card 2

Columns

1-8	Times expected between cutoff saw and defecting rip saw (CRRAT(1,1))
9-16	Times expected between cutoff saw and defecting rip saw (CRRAT(1,2))
57-64	(CRRAT(2,4))

Card 3

Columns

1-8	Time between defecting rip saw (#1) and rough planer (#1) (RPRAT(1))
9-16	Time between defecting rip saw (#2) and rough planer (#2) (RPRAT(2))
17-24	Time between planer (#1) and sort operations (PSRAT(1))
25-32	Time between planer (#2) and sort operations (PSRAT(2))

Card 4

Columns

1-7	Material cost per board foot of lumber input (COST)
8-10	Total number of part lengths to be processed (NSCHED)
11-13	Number of part lengths actively being cut (KSCHED)

Card 5 (Repeated once for each part length in the cutting order)

Columns

7-10	Alpha-numeric label used in printing results (LABL2)
11-20	Part length, in inches (PSCHED(1))
21-30	Part volume required, in board feet (PSCHED(2))
37-40	Priority for part lengths entering cutting bill (IPRIOR)
42-50	Final part widths for part lengths processed (FWID)
51-58	Panel widths for part lengths processed (FPWD)

Card 6

Columns

1-10	Labor costs, breakdown hoist, day, dollars per hour (CLABOR(1,1))
11-20	Labor costs, breakdown hoist, night, dollars per hour (CLABOR(2,1))
21-30	Labor costs, cutoff saw, day, dollars per hour (CLABOR(1,2))
31-40	Labor costs, cutoff saw, night, dollars per hour (CLABOR(2,2))
41-50	Labor costs, rip saw, day, dollars per hour (CLABOR(1,3))
51-60	Labor costs, rip saw, night, dollars per hour (CLABOR(2,3))
61-70	Labor costs, sort, day, dollars per hour (CLABOR(1,4))
71-80	Labor costs, sort, night, dollars per hour (CLABOR(2,4))

Card 7 (Repeated once for each number of cuts per board observed at the cutoff saw)

Columns

1-5	Number of cuts per board at the cutoff saw (NCUT)
6-10	First cell of cumulative distribution function (CDF) for number of parts cut (CPROB(1))
11-15	Number of parts associated with first cell of cdf (PCUT(1))
16-20	Second cell of cdf (CPROB(2))
21-25	Number of parts associated with second cell of cdf (PCUT(2))
26-30	Third cell of cdf (CPROB(3))
31-35	Number of parts associated with third cell of cdf (PCUT(3))
36-40	Fourth cell of cdf (CPROB(4))
41-45	Number of parts associated with fourth cell of cdf (PCUT(4))

Card 8

Columns

1-3	Total number of length-width combinations input to the data storage for MILLSIM 2 (ILENC)
-----	---

Card 9 (Repeated once for each part length-width combination input to MILLSIM 2)

Columns

5-8	Part lengths to be processed in MILLSIM 2 (LENC)
19-28	Final part widths for part lengths processed (FWIDC)
29-38	Panel widths per part lengths processed (FPWDC)
39-44	Part grade (IGRADE)
45-54	Percent of a specific length part's output that will be used as input in MILLSIM 2 (PLENCT)

Card 10 (This card and all subsequent cards are GASP IV input data, required to control simulation)

Columns

1-12	User's name (NNAME)
16-20	User's project number (NNPRJ)
21-25	Month (MMON)
26-30	Day (NNDAY)
31-35	Year (NNYR)
36-40	Number of runs (NNRNS)
41-55	GASP control variable (000002002002000) (LLSUP)

Card 11

Columns

1-5	Number of sets of statistics collected by COLCT (NNCLT)
6-10	Number of sets of statistics collected by TIMST (NNSTA)
11-15	Number of histograms (NNHIS)
16-20	Number of parameter sets (NNPRM)
21-25	Number of plots (NNPLT)
26-30	Number of random number streams (NNSTR)
31-35	Maximum allowable number of entries in NSET (NNTRY)
36-40	Number of attributes per entry in QSET (NNATR)
41-45	Number of files in NSET (NNFIL)
46-50	Dimension of NSET (NNSET)

Card 12

Columns

6-10	Index number (I)
11-18	Label associated with ith variable used in COLCT (LLABC)

Card 13

Columns

6-10	Index number (I)
11-18	Label associated with ith variable used in TIMST (LLABT)
21-30	Initial value of variable (SSTPV)

Card 14

Columns

6-10	Index number (I)
11-18	Label associated with ith histogram (LLABH)
26-30	Number of cells in Ith histogram (NNCEL)
31-40	Upper limit of first cell of Ith histogram (HHLOW)
41-50	Width of cell for Ith histogram (HHWID)

Card 15

Columns

1-5	Ranking attribute for file 1 (KKRNK(1))
6-10	Ranking attribute for file 2 (KKRNK(2))

Card 16

Columns

1-5	File 1 ranking system (1 = low-value first) (IINN(1))
6-10	File 2 ranking system (3 = first in-first out) (IINN(2))

Card 17

Columns

6-10	Parameter set number (J)
11-20	Parameter values defined by user (PPARM(J,1))
21-30	Parameter values defined by user (PPARM(J,2))
31-40	Parameter values defined by user (PPARM(J,3))
41-50	Parameter values defined by user (PPARM(J,4))

Card 18

Columns

1-5	Method of stopping (1 = stop at TTFIN) (MSTOP)
6-10	Key for clearing statistical arrays (1 = clear) (JJCLR)
11-15	Key for initializing variables (1 = initialize) (JJBEG)
21-30	Initial value of TNDW (TTBEG)
31-40	Ending time of simulation (TTFIN)
41-45	Key for initializing file system (JJFIL)
46-50	Random number seed (1) (IISED(1))
51-55	Random number seed (2) (IISED(2))
56-60	Random number seed (3) (IISED(3))
61-65	Random number seed (4) (IISED(4))
66-70	Random number seed (5) (IISED(5))

Appendix V—Input Instructions for MILLSIM 2

All data for MILLSIM 2 can be input using a standard 80-column, card-image format. Columns between 1 and 80 that are not specifically numbered in the following input formats contain no data and should be left blank.

Card 1

Columns

- | | |
|-----|---|
| 1-3 | Total number of part sizes to be processed (NSCHED) |
| 4-6 | Beginning number for part (NSBEG) |
| 7-9 | Ending number for part (NSEND) |

Card 2 (Repeated once for each part length in the cutting order)

Columns

- | | |
|-------|---------------------------------------|
| 1-10 | Length of part, in inches (ALEN) |
| 11-20 | Finished part width, in inches (AWID) |
| 21-30 | Panel widths, in inches (APWD) |
| 31-40 | Board-foot volume available (ABFT) |
| 41-50 | Board-foot volume required (RBFT) |
| 56-60 | Part grade (IGRADE) |

Card 3 (Repeated once for each part length-width combination in the cutting order. Immediately follows card 2 for each part length-width combination)

Columns

- | | |
|-------|--|
| 11-18 | Part width, mean (WD(1)) |
| 19-26 | Part width, standard deviation (WD(2)) |
| 27-34 | Part width, minimum (WD(3)) |
| 35-42 | Part width, maximum (WD(4)) |
| 43-50 | Part cost, mean (CD(1)) |
| 51-58 | Part cost, standard deviation (CD(2)) |
| 59-60 | Part cost, minimum (CD(3)) |
| 67-74 | Part cost, maximum (CD(4)) |

Card 4 (This card and all subsequent cards are GASP IV input data, required to control simulation)

Columns

- | | |
|-------|--|
| 1-12 | User's name (NNAME) |
| 16-20 | User's project number (NNPRJ) |
| 21-25 | Month (MMON) |
| 26-30 | Day (NNDAY) |
| 31-35 | Year (NNYR) |
| 36-40 | Number of runs (NNRNS) |
| 41-55 | GASP control variable (002022002202202)
(LLSUP) |

Card 5 (Same format as card 11 in MILLSIM 1)

Card 6 (Same format as card 13 in MILLSIM 1)

Card 7 (Same format as card 15 in MILLSIM 1)

Card 8 (Same format as card 16 in MILLSIM 1)

Card 9 (Same format as card 18 in MILLSIM 1)

Anderson, R. Bruce. **Programs for computer simulation of a crosscut-first furniture rough mill.** Gen. Tech. Rep. NE-97. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1984. 11 p.

Computer programs for simulating a crosscut-first furniture rough mill were developed to include all operations from the lumber breakdown hoist through the crosscut saws to the final machining-to-width on ripaws. The programs allow the user to measure the effects of changes in the factors affecting production costs and to determine total processing costs for individual parts leaving the furniture rough mill. A combined continuous/discrete FORTRAN-based simulation language, GASP IV, was used.

ODC 836.1; 796.1

Keywords: Computer program; FORTRAN; GASP IV; simulation; furniture rough mill

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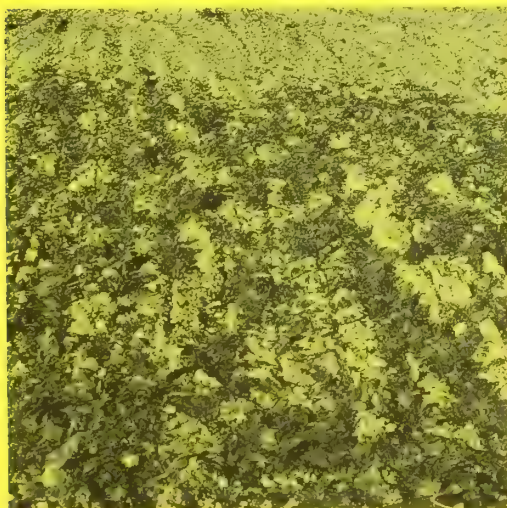
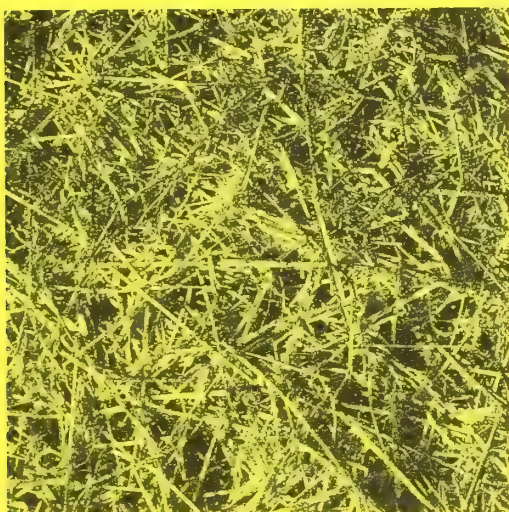
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A Guide for the Use of Organic Materials As Mulches in Reclamation of Coal Minesoils in the Eastern United States

Bernard M. Slick
Willie R. Curtis



Foreword

This report was made possible by funding from the U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, Ohio, and was completed under Contract No. EPA-IAG.DE-E764 by the U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Broomall, PA.

Extracting, processing, converting, and using energy and material resources create pollution. Because pollution impacts our environment and our health, new and increasingly more efficient pollution control methods are needed. Surface mining of coal results in the denuding of the ground surface. Without amendments and the rapid development of a vegetative cover, erosion from the mined area will occur. This report describes various organic materials and how they can be used in reclamation to better protect the surface and to speed the establishment and enhance the growth of vegetation. It also describes the physical and chemical changes that the organic materials impose upon spoils.

English units are used in deference to the majority of the readers for whom this guide is intended. An English to metric conversion table is on the inside back cover.

Information contained herein should interest surface-mine operators, land owners, reclamation contractors, reclamation associations, land resource managers, as well as local, State and Federal regulatory agencies. For further information, contact U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory, Resource Extraction and Handling Division, Extraction Technology Branch.

This report was reviewed by the Industrial Environmental Research Laboratory, U.S. Environmental Protection Agency. The contents do not necessarily reflect the views and policies of the U.S. Environmental Protection Agency.

DAVID G. STEPHEN
Director
Industrial Environmental Research Laboratory
Cincinnati, Ohio

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A Guide for the Use of Organic Materials

As Mulches in Reclamation of Coal Minesoils in the Eastern United States

Abstract

This guide includes a brief description of the environmental impacts of coal surface mining, the problems associated with disposal of organic wastes and a discussion of mulch in relation to erosion, soil properties, and plant growth. Organic materials that have potential use as mulches for revegetating surface-mined lands are identified and described. Selection criteria for organic materials, application methods, equipment, and requirements are explained. The principles and guidelines are applicable to past and current surface-mining operations; they may also apply to surface disturbances caused by surface mining for other minerals and by underground mining. This guide is not directed to the establishment of agricultural crops on areas designated as "prime farmlands", although much of the information herein will apply.

The Authors

At the time of manuscript preparation, Bernard M. Slick was landscape architect at the U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Berea, Kentucky 40403. Willie R. Curtis is Project Leader.

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Environmental Impacts

Coal Surface Mining

Much of our need for electrical energy is currently being supplied and will continue to be supplied from our coal reserves. As a result, each year in the humid Eastern United States, thousands of acres of land are surface mined for coal. Because of the current demand for energy, the foreign source of much of our oil, and the increasing prices of that oil, we are striving for energy independence by placing a greater reliance on coal as a fuel. Demand for coal is expected to more than double in the next decade. This will accelerate the growth of surface mining for several years to come and, at the same time, will continue to cause environmental disturbances.

Ecosystems in surface-mined areas are drastically altered and traditional land use patterns disrupted. Existing plant communities are removed from the mine site. Valuable soil and soil organisms often become buried or mixed during the movement and placement of overburden. Surface and ground water systems are polluted and flows disrupted. Wildlife habitat is eliminated or, at least, temporarily disturbed, and landform and vegetative modifications impact the visual quality and character of the landscape.

During surface-mining operations, the forces of nature are at work to destroy the mine site before it is ready for revegetation. The bare spoils are subjected to full exposure of the sun, wind, and rain. These forces, coupled with the constant pull of gravity, work very rapidly to tear down cut slopes and fills and to break up flat surfaces through water runoff and erosion.

One of the more serious impacts of erosion and sedimentation is degradation of the water resource. Results of hydrologic studies in mined watersheds have shown that before vegetation is established, erosion may contribute large quantities of sediment and toxic chemicals to various water courses, often resulting in a degraded aquatic ecosystem.

Organic Wastes

Approximately 800 million dry tons of organic waste materials are produced annually in the United States (Table 1) with almost half this amount generated in the East. Storage or disposal of concentrated quantities of some of these wastes is detrimental to the environment and poses an increasing problem and economic burden to our society. With continued growth in the population and in per capita waste generation, the volume of waste will increase considerably in spite of rising costs of energy and materials used in making products that generate wastes. This will increase the demand for better pollution control technology, better resource use and recovery, better disposal methods and sites, and more rapid improvement in environmental quality.

Table 1. Annual production of organic wastes in the
U.S. (USDA 1978)

Organic waste	Total production	
	<u>Thousand dry tons</u>	<u>Percent</u>
Animal manure	175,000	21.8
Crop residues	431,087	53.7
Sewage sludge and septage	4,369	.5
Food processing	3,200	.4
Industrial organic	8,216	1.0
Logging and wood manufacturing	35,714	4.5
Municipal refuse	145,000	18.1
Total	802,586	100.0

In the past, many wastes have been dumped on the land, emitted into the air, and discharged into waters. Improper disposal has led to adverse effects on our health and safety from fires and explosions; litter; breeding of disease vectors; deterioration of clean air by chemical emissions, particulate matter, or odors, and contamination of our surface and ground waters with toxic and pathogenic effluent discharges, landfill leachates, and acid rain. Overall, national efforts of the past decade and enactment of stringent laws such as the Clean Air Act and Federal Water Pollution Control Act to improve air and water quality are beginning to show results. However, increased emphasis has been placed on disposal of more of the wastes on land. This has become increasingly difficult due to scarcity of space for landfills, higher costs of land and disposal, tightening environmental standards, and increasing public opposition to disposal sites. Therefore, any economically feasible and environmentally constructive uses (such as mulches) that can be found for these waste products will be advantageous.

Definition of Mulch

A mulch is any suitable protective layer of organic or inorganic material applied or left on or near the soil surface as a temporary aid in stabilizing the surface and improving soil microclimatic conditions for establishing vegetation. This is in contrast to an amendment, which is an organic or inorganic material, such as lime, fertilizer, or manure that is incorporated into the soil "root zone" to make it productive or more productive of vegetation.

Reasons for Organic Materials on Mined Lands

Mulching has been used for years to protect the soil from erosion and excessive drying in agriculture, highway construction, roadside stabilization, and landscape development. However, mulching has been used in recent years in surface-mine reclamation to help establish optimum vegetative cover for site stability and productivity.

In the East, it has long been recognized that quick revegetation of freshly graded slopes or of any disturbed surface-mine areas is one of the most important means for effective control of excessive runoff, erosion, and sedimentation. However, physical and chemical characteristics of minesoils can cause adverse environmental and microclimatic stress conditions that hinder establishment and growth of plants.

The following stress conditions are the most detrimental to seed germination and subsequent plant growth: erosion, extreme diurnal surface and soil temperatures, lack of available moisture, and extremes in pH. These factors, along with lack of nutrients and organic matter, make it difficult to establish and maintain a diverse productive vegetative cover that will meet reclamation standards. To alleviate these conditions and make the minesoil more favorable for plant establishment and growth, the disturbed area microclimate must be modified. In addition to the usual fertilizers and lime used in the revegetation process, the application of a surface mulch can be used to modify plant growth conditions. The protective layer should maintain soil stability within acceptable levels during the time it takes the seedlings to emerge and become established, and then continue to enhance vegetative growth until the treated area is permanently stabilized. Also, mulches can be used on any disturbed and unprotected mined-surface area for temporary erosion protection. For example, when reclamation grading is completed and planting conditions are unfavorable for seeding, mulch can be used.

Organic mulches stabilize soils, reduce losses to erosion, enhance plant growth conditions, and aid in the construction of an improved minesoil profile. Straw, hay, and some hydromulches are most commonly used. However, recent restrictions on the disposal of various types of organic wastes (crop and wood residues, municipal and industrial wastes) have generated interest in their use as mulches or amendments for surface minesoils. Use of these resources in mine-reclamation systems will help not only to alleviate a disposal problem for the various residues and wastes, but also to control erosion while simultaneously protecting or enhancing the quality of our environment.

Scope of Guide

The guidelines, criteria, and information provided in this publication are directed primarily toward the use of organic mulches as an aid in preventing excessive soil loss and in revegetating lands disturbed by coal surface mining in the Eastern United States. More specifically, this area includes 19 states associated with the Appalachian, Eastern and Western Interior, Anthracite, and Lignite coal regions (Fig. 1). Organic wastes that have been used as mulches on mined lands are described. The selection and use of organic wastes for conservation purposes, mainly soil and watershed protection and enhancement of plant growth, are emphasized. The principles set forth in the guide apply mainly to current mining operations but are also applicable to revegetation of abandoned mine lands and other disturbed lands.

The information in this guide was derived from numerous sources, including research and administrative publications of Federal, State, and private agencies and organizations; direct communications with reclamation specialists in the surface-mining industry and with others involved in surface-mine reclamation research, administration, and application. Some of the mulching recommendations are based upon research conducted over the past several years by the USDA Forest Service scientists. References are listed in a bibliography and are not cited in the text.

The guide should aid in the revegetation of final graded slopes. Information contained herein should be used in conjunction with local expertise. The scope of this report is limited by available information on use of various organic wastes in surface-mine reclamation and is based on current understanding.

Revegetation Planning and Regulations

Mine operators should be aware of Federal and appropriate State regulations that pertain to the revegetation, mulching, and other soil-stabilizing practices of lands disturbed by coal mining. For example, Section 816.114 of the regulations promulgated under the Surface Mining Control and Reclamation Act of 1977 requires that each permit application contains a plan for revegetation, including mulching techniques, of the mined area. The plan should include a schedule of mulching activities such as the type of mulch to be used, the rate of application per acre, and the application time, method, and equipment.



Figure 1.--Coal regions of the Eastern United States: (1) Appalachian, (2) Eastern Interior, (3) Western Interior, (4) Anthracite, and (5) Lignite.

The regulations also include requirements for timely reclamation, period of operator responsibility, topsoil removal and redistribution, tree and shrub stocking standards, mulch anchoring, in situ mulch, chemical soil stabilizers, and land use considerations. These requirements may vary by State but will be at least as stringent as the Federal requirements. Thus, operators should consult State and Federal regulations as their first step in soil stabilization planning and revegetation.

ORGANIC MATERIAL FOR MULCHING MINED LANDS

Types and Sources

A wide variety of materials has been tested for mulching effectiveness. Organic mulches are usually preferred to inorganic mulches because they are nature's own materials, sometimes providing needed microflora and fauna, seeds, organic matter, and nutrients to the often sterile heterogeneous minesoils. Organic matter is recognized as one of the most important factors in building a good soil structure capable of retaining moisture and plant nutrients. Soil scientists have long recognized the importance of manure, crop residues, and other organic materials in maintaining or improving soil tilth. Very extensive literature exists on the effects of organic mulches on cropland soil conditions, runoff, erosion, and yield of crops, but considerably less information has been published on their use in mine reclamation.

Straw, hay, wood chips, bark, and some hydromulches are most commonly used in reclamation. All of these materials have been tested or observed on surface mine spoils and have been found to be effective in promoting plant growth. They are applied as surface mulches or incorporated into the rooting zone depending, primarily, upon the severity of the revegetation problem and site accessibility.

Available mulching materials can be identified (on the basis of their physical character) as fibers, solids, or liquids. Fibrous mulches are usually classified as long- and short-fibered. The long-fibered mulches are materials like straw, hay, shredded hardwood bark, and composted municipal waste. Short-fibered mulches are hydromulch, wood fibers and cellulose, paper, and agromulch. Solid mulches include animal manure, wood bark, wood chips, sawdust, shavings, and sewage sludge. Liquids are usually associated with hydromulch and animal, municipal, and industrial sewage wastes.

The various fiber, solid, and liquid mulches have specific attributes and limitations. Materials behave quite differently under different soil and climatic conditions. Long-fibered crop residues decompose rather rapidly but are generally more effective in reducing surface flow and trapping sediment than short-fibered mulches. However, the effectiveness of short-fibered mulches can be improved by combination with a tackifier or soil stabilizer. Softwood bark mulches enhance legume establishment and last longer than hardwood bark mulches that adhere better to the soil providing improved erosion control. Liquid sewage effluent lowers soil temperature as it evaporates but it has little or no erosion control potential compared to the more solid sewage sludge. Materials with desirable attributes can be combined to attain specific chemical and physical properties and to equalize cost and availability.

Four major categories of organic wastes are considered here: agricultural (crop and livestock residues), silvicultural (logging and wood manufacturing wastes), industrial, organic wastes and municipal (refuse and sewage sludge), or combinations of these. Each type functions in its own way to protect and build the soil and establish vegetation. For each kind of waste, information is reported on quantity generated, usage, and problems and constraints affecting usage. The data are presented for each major farm production region (Fig. 2) by summarizing information on organic waste materials from individual states. Information on those farm production regions east of the 100th meridian are applicable to this guide.

The following section lists and describes the mulch types in each category. Only those materials that are available in sufficient quantities to meet surface-mine reclamation needs will be reviewed in depth. Availability and distribution of materials vary with the distance from the source of supply and reasonable cost. However, one should be able to find one or more of the materials in any project area.

This information is provided to give the user a general idea of the type and effectiveness of organic waste products available for mulching minesoils. The basic characteristics of the most readily available materials are evaluated for erosion control and on-site physical, chemical, biological, and climatic variables that may affect soil stabilization, the establishment of vegetation, and the cost of achieving protection objectives after the site is mined.

Agricultural Residues

In the future, as U.S. farmers increase food and fiber production to meet domestic and world needs, greater volumes of livestock and cropland wastes will be produced (current annual volume is more than 600 million tons). Returning these agricultural wastes to the land has been a traditional practice of American agriculture. About 75 percent of the total annual production of organic wastes is associated with crop residues (53%) and animal manures (22%). About three-fourths of these two wastes is currently being applied to the land. It would be feasible and economical to use the remaining waste for surface-mine mulch.

Crop Residues.--Crop residues of cereal foods and fodder crops include stalks, stems, leaves, roots, cobs, hulls, chaff, pulp, and any other plant parts that remain after agricultural crops are harvested. According to a recent USDA survey, more than 430 million tons of crop residue are produced in the United States annually by 15 major crops (Tables 2 and 3). These crops account for more than 80 percent of the total crop residues produced. Of these, field corn, soybeans, and wheat account for 75 percent. Although most of these residues are returned to the soil, some could be available for use as surface-mine mulch.



Figure 2.--U.S. farm production regions (USDA 1978).

Table 2. Production and disposition of crop residues, by region (USDA 1978)
(Includes animal bedding wastes)

Region	Total annual production	Sold	Fed	Fuel	Returned to soil	Waste
	<u>Million tons</u>	<u>-----Percent-----</u>				
Northeast	11.183	3.8	29.3	0.0	66.4	0.5
Lake States	44.494	5.2	29.9	.0	64.8	.1
Corn Belt	173.011	.9	37.7	.0	61.4	.0
Northern Plains	81.526	3.0	21.3	.0	75.7	.0
Appalachian	17.279	.8	29.0	.0	69.8	.4
Southeast	13.530	1.3	19.6	9.0	59.1	11.0
Delta States	15.121	5.0	2.2	5.3	62.9	24.6
Southern Plains	32.728	2.1	25.9	.1	63.9	8.0
Mountain	20.002	4.3	6.3	.0	89.2	.2
Pacific	20.213	7.6	3.9	.0	81.5	7.0
National average		2.7	26.2	0.5	68.2	2.4
Total	431.087					

Table 3. Percentages of animal bedding wastes, by source and region (USDA 1978)

Region	Sources							Total annual production
	Dairy	Feeder beef	Sheep	Swine	Layers	Broilers	Turkeys	
	<u>Percent</u>							<u>Million dry tons</u>
Northeast	94.1	1.2	0.9	0.1	0.8	2.7	0.2	3.206
Lake States	93.3	4.1	.6	.5	.3	.0	1.2	4.612
Corn Belt	65.3	24.4	3.2	4.2	.6	.0	1.3	3.518
Northern Plains	64.5	16.1	13.9	4.7	.8	.0	.0	.712
Appalachian	82.6	3.1	1.5	1.4	1.0	7.6	2.8	1.399
Southeast	64.1	5.3	.0	1.2	3.0	25.7	.7	.853
Delta States	60.1	2.2	.0	.3	3.0	32.2	2.2	.642
Southern Plains	54.6	12.6	23.8	.4	.9	5.1	2.6	.740
Mountain	23.3	13.3	60.3	.3	1.6	.0	1.2	.577
Pacific	48.7	9.3	23.1	.2	6.2	6.0	6.5	.536
Subtotal								16.804
Additional bedding wastes (geographical distribution data not available):								
Beef cows								4.000
Horses								3.000
Total								23.804

Most of the crop residues listed above are grouped as straw, stalks or stover, corn cobs, stems and leaves, and hulls:

Straw

Barley
Flax
Oats
Rice
Wheat

Stalks or stover

Broom corn
Castor bean
Field corn
Hemp
Kaffier
Pop corn
Sorghum
Sugar cane
Sunflower
Sweet corn
Tobacco

Corn cobs

Field corn
Pop corn
Sweet corn

Stems and leaves

Dry beans
Peanut
Potato
Soybeans
Sugar beet

Hulls

Buckwheat
Cocoa
Cotton (seed and lint)
Peanut
Rice (whole or ground)

Straw comes from various cereal crops. Stalks or stover are usually the residue of corn, cane, sorghum, and similar whole or shredded stalks. Hulls are usually by-products from industry and come from such plants as cocoa, cotton, and peanut.

Many of these materials need to be reprocessed before they can be used as a mulch. Bulky pieces, such as corn and cotton stalks, can be reduced in size by grinding, crushing, flailing, shredding, or milling (hammer mill). Others need to be dried before being transported and applied. Packaging is expensive and may not be justified unless there exists a well-developed market for the mulch.

It may be necessary to restrict the use of crop residues if: (1) the danger of transmitting a plant disease is high; (2) they contain undesirable seed that will compete with the desired species; and (3) they have an excessive quantity of noxious weed seeds, that could be a menace to surrounding farmland.

Straw is the crop residue most commonly used for mulch. Other residues yielding varying degrees of success include bran, crushed corn cobs, rice, straw, cocoa, and peanut hulls. The use of these materials is limited, and their importance will be restricted to areas in which they are produced.

Hay.--Hay is a production resource and not considered a waste unless there is a surplus due to extremely favorable growing conditions and lack of demand. It is included here because various grass and legume crops are commonly used as mulches:

Grass

- Bluegrass
- Coastal Bermuda
- Orchardgrass
- Perennial rye
- Redtop
- Tall fescue

Legume

- Alfalfa
- Birdsfoot Trefoil
- Cowpea
- Crownvetch
- Lespedeza
- Peanut
- Red clover
- Soybean
- Sweet clover
- Timothy

In addition to hay that may be purchased, many mining companies are using cuttings of herbaceous plantings from their own previously reclaimed areas as mulch for new reclamation projects (Fig. 3).

In-Situ Vegetative Mulches.--In-situ vegetative mulches are a special category of crop residues. Quick-developing annual grasses such as Japanese and pearl millet, rye, sorghum, and wheat can be used alone as in-situ mulch or in conjunction with another mulch. The grass provides a ground cover while it is growing and continues to protect the site after it has matured and died. In-situ mulches may provide effective protection for a year or more. A disadvantage is that this type of mulch cannot be established in all seasons or on all areas.



Figure 3.--Baling hay on reclaimed land.

Animal Wastes.--Animal waste refers to feces and urine (manure) excreted by various livestock (about 89 percent of all manure is produced by dairy and beef cattle and horses) and poultry produced by the United States agricultural industry. Bedding and litter sometimes used to absorb moisture and facilitate handling manure as a solid material were considered under crop residues (Tables 2 and 3).

Livestock and poultry manure represent about 22 percent of the total of all organic wastes produced in the United States or 176 million tons on a dry-weight basis (Table 4). About 70 million tons (39 percent) of this are produced under confined conditions. The remaining 105 million tons (61 percent) are excreted on pasture, rangeland, or cropland.

Approximately 90 percent of all manure generated under both confined and unconfined conditions is used as a production resource on land. Most of the remaining 10 percent or about 18 million dry tons is disposed of as waste and could be used on minelands.

Manures are available in solid, slurry, or liquid forms depending on the type of waste-management treatment system used to collect, treat, and store waste. "Solid" is defined as having total solid content greater than 25 percent (wet-weight basis); "slurry", 8 to 30 percent; "liquid", less than 10 percent.

Manure has been used as a production resource on land for many years because it improves soil fertility and tilth when applied at rates within crop fertilizer requirements. Land application of manure is limited primarily by the economics of collection, storage, transportation, and application. Transportation costs and land availability are important constraints on efficient use of manure as a mulch and fertilizer.

Silvicultural Residues

The growing demand for all timber products increases volumes of logging and wood manufacturing residues, which presently amount to about 100 million tons a year. A good share of this is generated from the growing stock of hardwood and softwood commercial timberland in this country. Three-fourths of this growing stock is in the Eastern United States (about equally divided between north and south).

Logging Residues.--Logging residue is the debris left in the woods following intermediate cuttings, understory removal, salvage operations, and the removal of marketable products. It includes limbs, needles, leaves, diseased or decayed wood, and noncommercial residual stands. Each year over 26 million tons of logging residues are generated in the United States with over 70 percent of it in the East (Table 5). In the East, residue volumes average about 700 cubic feet per acre. Residues from a logging operation in the area of active mining could be used for mulch if the residues could be collected and transported economically.

Table 4. Annual production of animal manures, by region (USDA 1978)

Region	Dairy cattle	Beef cattle	Horse	Sheep and goat	Swine	Broiler	Chicken other than broilers	Turkey	Duck	Total
<hr/> <u>Thousand tons</u> <hr/>										
Northeast	5,666	1,317	1,555	26	177	1,223	586	54	26	10,631
Lake States	8,536	3,887	1,782	58	804	25	298	406	4	15,800
Corn Belt	4,400	18,874	2,646	149	4,041	59	645	318	10	31,143
Northern Plains	1,458	18,451	1,430	163	930	2	117	32	0	22,584
Appalachian	2,424	7,904	2,848	42	711	494	423	375	1	15,221
Southeast	1,227	8,679	1,994	1	432	1,001	943	56	0	12,332
Delta States	860	5,384	1,184	3	128	869	468	138	0	9,034
Southern Plains	1,193	20,660	3,494	472	160	210	192	141	0	26,522
Mountain	1,307	12,810	2,800	558	110	0	112	82	0	17,777
Pacific	2,987	5,521	3,501	192	42	142	619	261	2	13,265
Alaska, Hawaii, and Puerto Rico	266	508	64	1	14	2	15	0	0	870
Total	30,323	101,994	23,296	1,664	7,549	4,026	4,418	1,863	43	175,176

Table 5. Logging residues generated annually, by region^a (USDA 1978)

Region	Logging residues		
	Softwoods	Hardwoods	Total
	-----Thousand tons-----		
Northeast	1,006	2,639	3,645
Lake States	49	661	710
Corn Belt	5	983	998
Northern Plains	Trace	24	24
Appalachian	516	3,647	4,163
Southeast	2,209	2,203	4,412
Delta States	1,113	1,773	2,886
Southern Plains	308	274	582
Mountain	1,462	7	1,469
Pacific	6,508	656	7,164
Hawaii, Alaska	74	0	74
Total	13,250	12,867	26,117

^aRegional estimates were obtained from the 1976 Resource Planning Assessment (RPA) data. The RPA data were transformed from volume to mass by a conversion factor of 30 lb/ft³ for softwoods and 44 lbs/ft³ for hardwoods. These data do not include stumps, residues more than 4 inches in diameter, and rough and rotten trees.

Another potential source of residue is the waste generated from mine-clearing operations. It has been estimated that approximately 90 percent of surface mining in Appalachia occurs on forested lands. Most of this timber removed during mining has been wasted. The Federal Surface Mining Control and Reclamation Act limits the options available to a surface-mine operator for the disposal of woody vegetation removed during the clearing operation. Pushing vegetation over the outslope for a sediment filter at the toe of the slope is no longer permissible. Burying on the bench next to the highwall is wasteful and can reduce stability in fills.

All commercially attractive timber should be removed during site preparation. Woody residues (tops, branches, under brush) remaining could be chipped on-site for use as mulching material in reclamation operations (Fig. 4). The main drawback to this practice is that it may not be economical.

Wood Manufacturing.--Over 70 million tons of residue--slabs, edgings, chips, shavings, bark, sawdust, and other unused wood wastes--accumulate in this country each year (Table 6). Much of this material is allowed to remain where it accumulates. The problem of disposal has plagued wood-utilizing industries across the country. In the past, sawmill operators disposed of their surplus residues by indiscriminate dumping or burning. Since 1970, the burning and dumping of waste have been eliminated by emission and sedimentation standards. Most sawmills, however, continue to dump their waste in unused areas. Properly utilized, those residues could be of considerable value to reclamation and would help alleviate disposal problems. Wood residues could contribute much-needed organic matter and should be utilized for humus maintenance in every location where economically feasible.

Wastes generated in the manufacture of paper and paper products are considered industrial organic wastes. More than 85 percent of these residues are utilized for a variety of products by the pulp and paper, particle board, and fiberboard industries. However, the annual production of over 10 million tons is available for other uses and has greater potential than that of logging residues (except those from mine clearing) for use as mulches.

Wood organic matter has been used for over 20 years. However, only recently has there been a rapid, widespread and increasing interest in the utilization of silvicultural residues for mulching in reclamation. The following is a list of silvicultural residues by type and form:

Bark (hardwood, softwood)

- Ground (soil conditioner)
- Shredded
- Chunk
 - Small (chip)
 - Medium (nugget)
 - Large (chunk)

Woodchips (hardwood, softwood, mixed)

- Small (chip)
- Medium (nugget)
- Large (chunk)



Figure 4.--Whole-tree chipper.

Table 6. Wood manufacturing residues production in the United States and how these residues were used in 1970 and 1976^a (USDA 1978)

Item	Softwoods		Hardwoods		All species	
	1970	1976	1970	1976	1970	1976
Total wood manufacturing residues	45,540	52,140	16,918	17,336	62,458	69,476
Used for pulp	22,710	28,560	5,698	7,876	28,408	36,436
Used for fuel	8,985	10,230	2,794	2,552	11,779	12,782
Used for other products	3,615	8,175	1,584	2,486	5,199	10,661
Unused	10,230	5,175	6,842	4,422	17,072	9,597

^aEstimates were obtained from the 1976 Resource Planning Assessment (RPA) data. The RPA data were transformed from volume to mass by a conversion factor of 30 lb/ft³ for softwoods and 44 lb/ft³ for hardwoods.

Sawdusts and/or shavings

Green
Composted

Leaves

Loose
Baled

Pine straw

Needles

Evaluation of wood residues as mulches has shown them to be a vital resource that could be used extensively in reclamation of surface-mine spoils. Hardwood tree species used for bark mulches are: ash, basswood, beech, birch, black walnut, cherry, elm, gum-red, hickory, oak (black, chestnut, post, red and white), maple, sycamore, and yellow-poplar. Softwood species used are: red cedar, hemlock, pine (loblolly, long leaf, short leaf, slash, Virginia, and white).

Municipal Wastes

The two types of municipal wastes and their sources are:

Solid waste (composted)

Residential
Institutions
Offices
Industry
Shops
Rural

Sewage sludge

Residential Systems
Septic

Community and Industrial Systems
Solid
Slurry
Liquid

Increased product packaging and urbanization are having their effects on the volume of refuse and sludge produced. Each is directly related to per capita consumption and use with quantities steadily increasing in spite of a reduction in birth rate. By 1990, wastes from these two sources will amount to over 250 million tons annually.

Solid Waste Refuse.--The Council on Environmental Quality estimates that about 200 million tons of municipal refuse are generated each year in the United States. Of this, about 145 million tons are collected. About 30 percent of the total is generated in rural areas and only about 8 percent collected. Trash and garbage production is estimated at 1,100 to 1,700 pounds per person per year, and quantities generated per capita are increasing steadily.

The collectible portion of solid waste generated is, by weight, about 70 percent biodegradable organic material consisting mostly of paper products, food residues, and yard trash, which includes lawn, shrub, and tree clippings and trimmings. The remainder is nonbiodegradable metal, glass, and plastics. The organic component has potential value as a mulch material. The composition of municipal refuse is:

<u>Refuse category</u>	<u>Range of reported values, percent</u>
Paper	28-30
Paperboard	7-24
Garden wastes	7-35
Garbage	2-9
Metal	6-10
Aluminum	0.3-1
Glass	3-10
Cloth	1-3
Plastics	1.5-3
Fats and oils	2-6
Residue (ashes, dirt, etc.)	3-20

Currently most of this refuse is disposed of in sanitary landfills. However, it has become necessary, though increasingly difficult and costly, to locate and obtain public consent for new landfill sites. Application of refuse on the land is a possible alternative to new landfills because it utilizes wastes for a beneficial purpose.

Use of the organic component of municipal refuse as a mulch is practicable only if it is well sorted and shredded. Without such processing, it is neither feasible nor desirable to apply to land. To date, efficient and economical methods for separating nonbiodegradable components from the useable organic fraction have not been developed. Therefore, land application at this time must be considered marginal.

Refuse intended for land application is usually composted to enhance its value as a mulch and to facilitate handling and blending of material with organic wastes such as bark.

Sewage Sludge.--The current annual production of sludge in the United States is 4.3 million dry tons. According to the 1978 USDA special report, "Improving soils with organic wastes", annual production, in thousand dry tons, of sludge by region is:

Northeast	1080.1
Lake States	444.1
Corn Belt	897.0
Northern Plains	76.0
Appalachian	321.5
Southeast	309.0
Delta States	125.3
Southern Plains	295.6
Mountain	192.5
Pacific	536.7
Hawaii, Puerto Rico, Alaska	21.7
<hr/>	
Total	4,299.5

Sludge production is expected to increase more than 25 percent by 1990 to about 5.5 million dry tons (assuming a population increase in the United States of 14 percent). An additional 0.69 million dry tons is septage produced from individual on-site residential treatment facilities. This septage is expected to reach 1 million tons by 1990. More than 71 percent of the population producing 60 percent of the sewage is served by municipal sewers. The production equivalent of dry sludge per capita per day is 0.12 pounds. In addition to increased waste due to population increases, mandated improved wastewater treatment will also generate extra sludge.

Various kinds of wastewater and solids have been applied on land for a long time in many areas of the world. In the United States there are three types of sewage waste--solid, slurry, and liquid--that are produced in the three steps of the wastewater treatment process. Solid or sediment from primary treatment is defined as that with total solid content greater than 25 percent (wet weight); slurry or activated sludge from secondary treatment, 8 to 30 percent; and liquid or effluent from tertiary treatment, less than 10 percent (Table 7).

Table 7. Sludge solids content and handling characteristics

Type	Solids content	Handling methods
	<u>Percent</u>	
Liquid (slurry)	1-10	Gravity flow, pump, tank transport
Semisolid ("wet" solids)	8-30	Conveyor, auger, truck transport (watertight box)
Solid ("dry" solids)	25-80	Loader, conveyor, truck transport (box)

There may be some potential problems and constraints associated with sludge disposal on mine spoils. Large-scale application of sludges depends on the resolution of concerns related to public acceptance: objectionable odors, pathogens and parasites, heavy metals uptake by plants, toxic organic compounds, nutrient (nitrogen) content of sludge runoff, pollution of streams and groundwater, and government regulations.

Most of the potential physical, chemical, and biological problems can be minimized or eliminated if waste is composted before use. Problems of a political nature can be alleviated, or at least modified, by appropriate information and education.

The proper use of sewage sludge on surface-mined land makes it possible to grow a wide variety of agronomic and horticultural crops as well as many forages. Where adequate supplies of sewage sludge or effluent exist, they should definitely be considered in view of the documented performance on mine soils.

Municipal sewage sludge could be used in reclaiming many of the 1.1 million acres of abandoned surface-mine land in the United States (Table 8). More than 97 percent of this land is concentrated east of the 100th meridian (Fig. 5). Some of this land has the most hostile of all environments for plant establishment and growth because of spoils that are highly acid and with toxic levels of iron, aluminum, and manganese; droughty; low in fertility; and extremely high in summer surface temperature. The harsh site conditions of some of these abandoned spoils have been ameliorated and productivity improved by irrigation treatments with sewage effluent and liquid digested sludge.

Industrial Wastes

Industrial organic wastes considered suitable for land application come from the following industries: textile finishing, paper and allied products, organic fibers (noncellulosic), pharmaceutical (waste mycelium), leather tanning and finishing (vegetable), petroleum refining, and miscellaneous organic chemicals. Pulp and paper, petroleum refining, and the miscellaneous organic chemical sludge groups are identified as the largest contributors of organic wastes. Although the estimated quantity of industrial sludge considered suitable for land application is more than 9 million dry tons per year, this is only a little more than 3 percent of the total annual production in the United States (Table 9). These organic residues are in addition to those being discharged into and recovered from municipal-waste treatment systems.

Other industrial wastes used or tried as soil amendments are macerated paper, digested paper, pulp-mill chip washings, waste sulphate liquor solids, wood fiber and cellulose, seed refractory screenings, and hulls from crops.

Land application of industrial organic wastes has been practiced on a limited scale usually as means of disposal rather than as an aid to soil and plant growth improvement. It is possible that some industrial wastewater and sludges can be collected, processed, transported, and applied to land using the existing methods applicable to municipal sludges or wastewaters.

Table 8. Acreage of abandoned mine lands in Midwest and East (USDA 1978)

State	Acres
Alabama	72,300
Arkansas	5,600
Georgia	1,700
Illinois	118,700
Indiana	25,900
Iowa	14,000
Kansas	41,300
Kentucky	101,600
Maryland	2,800
Michigan	100
Missouri	70,700
Ohio	196,700
Oklahoma	36,100
Pennsylvania	240,000
Tennessee	29,600
Texas	3,300
Virginia	23,700
West Virginia	84,900
Total	1,069,000

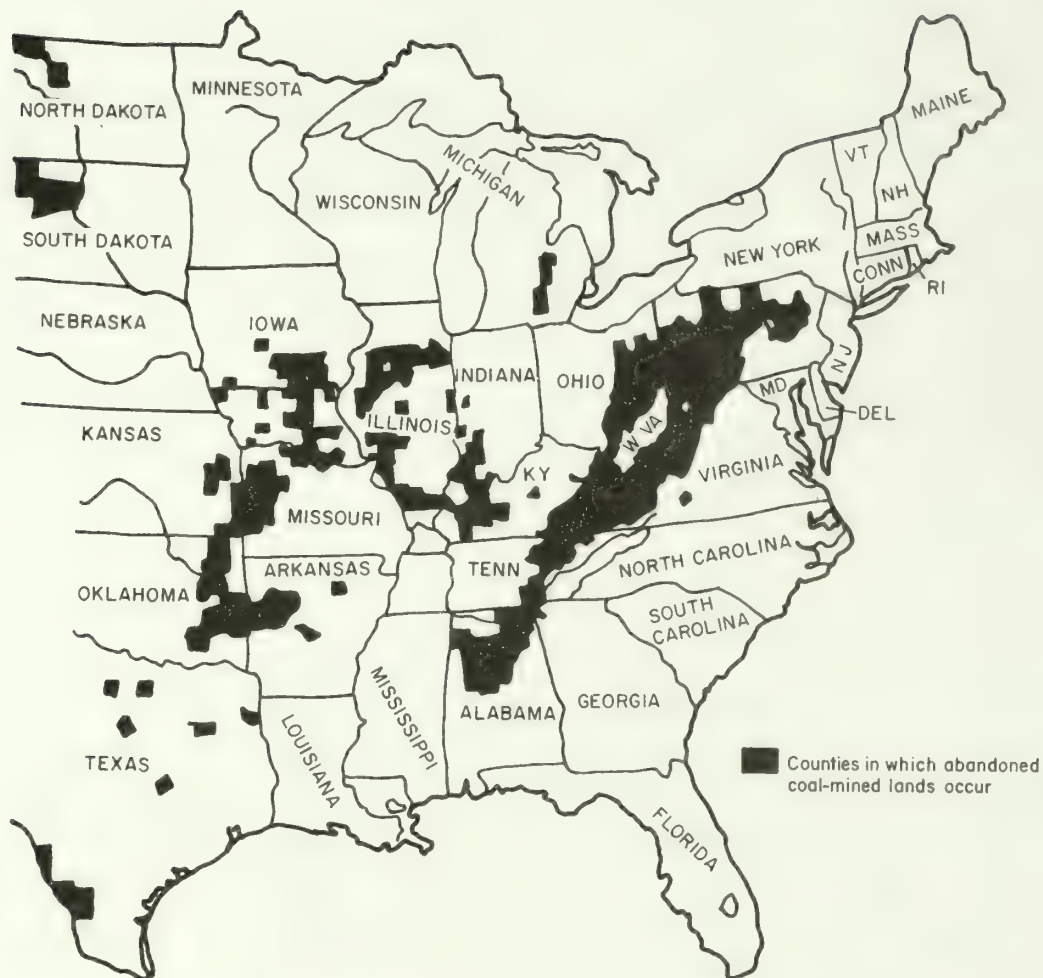


Figure 5:--General location of abandoned coal-mined land east of the 100th meridian (USDA 1978).

Table 9. Estimated annual production of industrial wastes suitable for land application in 1975, 1980, and 1985, by industry (USDA 1978)

Industry	Waste type	1975	1980	1985
		<u>Thousand dry tons</u>		
Textile finishing	Secondary wastewater sludge	42.9	93.5	198.0
Paper and allied products	Primary wastewater treatment sludge	1,870.0	2,090.0	2,310.0
Organic fibers, noncellulosic	Secondary wastewater sludge	5.3	8.0	10.8
Pharmaceutical	Waste mycelium	69.3	89.1	110.0
Leather tanning and finishing (vegetable)	Secondary wastewater treatment sludge	.9	.8	.7
Petroleum refining	Nonleaded product tank bottom	45.1	56.1	68.2
	Waste biosludge	44.0	55.0	68.2
	API separator sludge	37.4	46.2	57.2
	Dissolved air flotation float	31.9	40.7	49.5
	Slop oil emulsion solids	18.7	23.1	28.6
	Crude tank sludge	.4	.5	.7
Miscellaneous organic chemicals	Wastewater treatment sludges	6,050.0	9,983.0	12,251.9
Total		8,215.9	9,983.0	12,251.9

Caution must be exercised in the application of some industrial organic wastes to lands because the original product or the various processing additives may result in materials that are potentially toxic to plants, animals, or humans. Serious constraints that limit their desirability may be associated with specific wastes: high concentrations of one or more heavy metals; hazardous or phytotoxic chemicals; soluble salts, especially sodium; very high carbon to nitrogen (C to N) ratios; and low concentrations of nutrients essential for plant growth. Any particular industrial organic waste considered for land application must be evaluated on its own merits, based on suitable analytical data and site-specific management.

Food Processing Wastes.--Over 3.2 million dry tons of food processing wastes are produced annually from fruit, vegetable, seafood, sugar, fats and oils, and dairy products. Although these liquid wastes are compatible with the environment, it is not likely that they will be available to any appreciable extent for application to disturbed lands. Use of these wastes as an animal feed and for by-product manufacture is expected to increase with developing technology, significantly decreasing the amount of waste available from these sources. Less than 16 percent, or 500,000 tons of the wastes produced, is currently available for land application. Food processing wastes used or tried as soil surface mulches are sugar beet pulp and bagasse.

MULCH SELECTION

In developing a reclamation plan, the first task following the selection of a plant species is to choose a mulch. Correct material selection is difficult because no one mulch material is best for all situations. The physical, chemical, and biological properties of soils, the degree and length of slope, the exposure, and climate are important considerations. Mulches can sometimes cause problems including nutrient and waste immobilization, germination inhibition, potential invasion of weeds, and the attraction of unwanted organisms and plant diseases. A material should be chosen only after consideration of these potential problems.

Not all materials are adapted to all sites; a number of factors affect adaptability. Although these factors are considered separately, it is their combined influences that determine the need for a mulch and the potential of the selected material. The selection of one type of material over another involves not only consideration of the material itself but also a trade off among the many interfacing factors. In choosing a mulch, consider all of the following criteria as a basis for comparing and evaluating materials, and determine which attributes are most important in each particular situation, then choose the material that most nearly satisfies requirements and needs.

Intended Use

When planning a mulch treatment and selecting equipment suitable for its application, one must be familiar with both legal requirements and the revegetation objectives of the project. The type and amount of mulch material selected depends on site conditions, the vegetative cover being sought and approved for the postmining use, and the regulatory requirements for erosion control.

Mulch is used to cover and protect the soil surface and seedbed; to control erosion on steep slopes and in drainage ways; and as a plant mulch to conserve moisture, protect surface roots, and to control unwanted vegetation around tree and shrub seedlings. The advantages of mulching exceed the protection it provides. Mulching also can be used as a decorative ground cover to improve the appearance of an area when landscaping, and in planting beds around mine administrative facilities and other structures frequented by the public. Mulch may be required for one or all of these purposes.

Surface Protection

All mulches provide some protection to the soil surface if applied in sufficient quantities. Application rates that provide 1/4 to 2-inch-thick layers, depending on the mulch used, are generally adequate. The range of effective application rates reflects variability in character of mulch materials used, corresponding percent of surface area covered, site conditions, and seasonal weather patterns.

The most important function of a mulch in surface protection is to provide a protective shield and obstruct water from the soil surface. Mulch will neutralize wind saltation and kinetic energy of raindrop splash, thereby dissipating the transport energy and abrasive action of wind and moving water. A mulch that bonds to the soil surface helps to bind the soil particles together to form a mass that is less easily displaced. The most effective mulch is one (such as bark) that provides bulk and protective cover and good adherence to the soil surface with resistance to blowing or washing away.

Considerable care should be taken to see that mulch material is evenly spread over the area. A partially covered surface is less efficient in protecting the soil surface from falling rain and controlling soil washing. As the percent of cover increases, runoff decreases. The effectiveness of mulch in stabilizing the soil surface is a function of coverage and durability.

Usually, the minimum amount of mulch coverage needed for surface protection is 75 percent. It has been shown that, when compared to a bare site, a mulch coverage of even 50 percent reduced the erosion rate by 35 to 40 percent for a wide range of steepness and length of slopes. For example, on a simulated 15 percent slope, one-quarter ton per acre of straw mulch with only 34-percent surface coverage reduced erosion to about one-half that from an unmulched treatment. One-half ton per acre, or 49-percent coverage, reduced erosion to one-third or less. Four tons per acre, or 100 percent coverage, reduced it by more than 95 percent.

It has been shown that 1-1/2 tons per acre of crop residue on the surface reduced soil erosion on cropland to half that of conventional tillage without residues. If crop residue is used for surface protection against erosion, coverage should equal 2 tons per acre or more.

Seed Cover

Good soil and water control is attained by establishing sods quickly, thus the most desirable mulches should encourage rapid germination, augment seedling population, and stimulate seedling growth. Mulch should be applied at the optimum rate and depth that will provide the necessary protection for the soil surface and encourage seed germination.

Mulches used as cover on new plantings reduce evaporation of moisture from the layer of soil in which young germinating seedlings are becoming established. However, at no time should mulch replace the soil as a seed cover. Seed covered with soil to the proper depth is essential, especially during dry periods. Soil coverage assures that an organic mulch will not take moisture away from seed and cause poor germination.

In establishing vegetation, a 100-percent coverage of mulch is more important than weight or volume needed for erosion control. Uniform application is required to effect complete and even revegetation.

In the germination and establishment of grasses, legumes, and direct seeding of woody vegetation on exposed soil surfaces, the important factors of a cover mulch are depth, type, and particle size of material. Mulch depth must be thin enough to avoid smothering emerging seedlings. Particle size must be large enough to keep the cover sufficiently loose and open and free from compaction.

Erosion Control

A vital function of a mulch is to reduce or prevent surface erosion by shielding, absorbing, and dissipating energy. Steep, bare, unvegetated minesoils are subject to high rates of erosion. Therefore, special efforts to prevent surface erosion are warranted, especially because repair of erosion damage is one of the most expensive recurring costs on mined sites.

Vegetating disturbed areas as quickly as possible is one of the most important and practical means of preventing excessive erosion. However, when site conditions are such that vegetation alone cannot withstand microclimate and imposed stresses of erosion, mulch can be used to reinforce vegetation measures. A properly selected mulch used with other good management practices is the most popular means of providing slope stabilization until a vegetative cover is established.

The objective of mulching is to make the soil surface rough, to minimize soil detachment, and to impede overland water flow thus reducing its volume and velocity and aiding water infiltration.

To prevent erosion, mulch must adhere to the soil. A mulch that makes a good contact with the ground reduces the potential for detachment and transport of soil. The various type of mulch can either physically block or check the overland movement of soil particles. Many solids (chunks) or fiber to the square foot decrease erosion because each particle of mulch becomes a tiny dam and acts as an obstruction to flowing water or wind detachment. The longer the fiber length the greater is the effectiveness of mulch in erosion control. Straw placed across a slope creates a dam and reservoir or ditch check in which sediment collects and develops into a miniature step or bench. This not only reduces the erosive power of the water, but also provides time for more of the water to seep gently into the soil. In torrential storms, mulch must be anchored to be effective.

Natural erosion proceeds at a very slow rate. Approximately 0.1 to 1.0 ton per acre of sediment is lost per year from protected watersheds. Agricultural erosion occurs at the rate of 0.3 to 6 tons per acre per year. The rate of erosion from construction activities ranges from 3 to 200 tons per acre per year. Mine operations that will continue for more than 2 years should try to maintain a sediment yield of not more than 5 tons per acre per year.

Wind erosion occurs primarily when the moisture content is lowered during drought periods. Low moisture content enables the wind to detach and transport light clay particles. When the wind becomes laden with soil particles, its abrasive action is increased. Particles eroded by wind are less than 0.02 inch in diameter. More than 93 percent of the total soil movement by wind takes place below a height of 1 foot, and 50 percent or more probably occurs within 2 inches of the ground. Properly anchored mulches may reduce surface wind velocity and lessen particle movement and dust.

Plant Mulch

The harsh microclimate of minesoils is often detrimental to the establishment of vegetation, especially shrubs and trees. Where soils are droughty or the effective rooting zone is shallow, heavy applications of mulch help to: conserve moisture, insulate shallow rooted plants from heat or freezing, and inhibit competition from unwanted weeds and other herbaceous vegetation. A good mulch for individual shrub and tree plantings, groups, and row plantings should hold water, be coarse, porous and nontoxic.

In addition to protecting the delicate plant roots and soil organisms from the direct influence of excessive heat and drought in summer, the effects of alternate freezing and thawing must also be considered. Frost action along with water thawing is responsible for some of the physical weathering which takes place in minesoils. As ice forms in rock crevices, it causes the rock to disintegrate. Similarly, alternate freezing and thawing subjects spoil aggregates and clumps to pressures and, thus, alters the physical set up in the minesoil. Freezing and thawing of the upper layers of soil can also result in so-called heaving of perennial plants. Herbaceous as well as woody-plant crowns can be exposed as a result of this type of action during the winter and early spring months. This action, which is most severe on bare, imperfectly drained soils, can drastically reduce vegetative stands. It has been found that application of a mulch reduces frost heaving of young seedlings.

Site Characteristics

A mulch should be tailored to the characteristics of the site on which it is to be used. Evaluation of topographic and geologic factors requires information on slope gradient and length, aspect (micro and macro slope), soil type, roughness, and erosion potential because they influence the ability of the mulch material to adhere to the site and its ability to withstand the stresses of erosion and traffic. This involves a review of information from the premining investigation of existing site features and conditions and, if necessary, a thorough field investigation of the site and surrounding areas. Consultation and advice on runoff, soil transport, and ground-water pollution potential may be obtained from USDA Soil Conservation Service.

Slope

Topographic considerations for erosion control, vegetation establishment, and land use include the allowable length and steepness of slope. Slope steepness and length each significantly affect the erosion rate and runoff velocity. As the steepness and length of slope increase, there is a corresponding rise in the velocity, turbulence, and the volume of surface runoff, resulting in greater erosion unless control measures are taken.

The carrying capacity of moving water increases as its velocity increases. Increased velocity associated with steep slopes causes more sediment to remain in suspension than that on lesser slopes. If the flow velocity is doubled due to increasing the degree and length of slope, the water will be able to transport soil particles 64 times larger and carry 32 times more material in suspension.

Long and steep slopes usually erode more rapidly and are more difficult to vegetate and to maintain than gentle short slopes and level areas. Long unbroken slopes of moderate steepness on gently rolling terrain suffer more erosion than steep but very short slopes. For equal areas, doubling the length of a slope increases the soil loss by a factor of 1.5. Long slopes allow surface runoff to concentrate creating rill and gully erosion channels (Fig. 6) that cause inconvenience and loss of efficiency with post-mine land use equipment.

Mining often results in steep slopes that are difficult to stabilize with vegetation. Mulch and vegetation techniques are usually limited to slopes of 2:1 (50 percent or 26-1/2 degrees) or flatter, and a slope of about 4:1 (25 percent or 14 degrees) is the maximum for contour operation of reclamation machinery.

We used the following classifications for slopes.

<u>Slope</u>	<u>Steepness</u>			<u>Length</u>	
	<u>Ratio</u>	<u>Percent</u>	<u>Degree</u>	<u>Slope</u>	<u>Feet</u>
Flat	10:1	10	5.75 or less	Short	33 or less
Rolling	3:1	33.33	18.5	Medium	66
Steep	2:1	50	26.5	Long	100 or over

On a 4 percent 40- to 70-foot slope, the erosion rate is relatively low even without mulch. Sediment was reduced to below 5 tons per acre on a 20 percent 150 foot slope where 25 tons per acre of mixed hardwood chips with 100-percent ground cover were subjected to 2-1/2 inches of intense rainfall.

Most mulches lose effectiveness as slope increases. For example, a 20 percent 150-foot slope with 95-percent cover of 2-1/2 tons per acre of straw eroded at a rate of nearly 70 tons per acre. Straw mulch was unsatisfactory on this slope because of rilling underneath. The same rate of straw effectively controlled erosion on slopes less than 20 percent.



Figure 6.--Rill and gully erosion.

On a 33-1/3 percent slope, 20 cubic yards per acre of shredded hardwood bark did not satisfactorily control erosion under a simulated 6- to 9-inch rainfall per hour, but 25 to 30 cubic yards per acre did reduce erosion markedly. A rate of 40 to 50 cubic yards per acre loose measure was even better and is the minimum rate of bark recommended.

If soil movement on steep slopes is to be controlled or minimized in the short term, it is absolutely essential that mulch material be anchored to the surface or partially incorporated into the minesoil. In relatively level areas, the application of a mulch should be optional if adequate water or moisture is available and the potential for erosion is minimal.

Aspect

Aspect (exposure) is the direction that a slope faces. Depending on the site conditions, aspect affects solar radiation loads, growing season length, and the establishment of vegetation, thus affecting the selection of mulch for mined areas. Contrasts in exposure to sunlight, degree of slope, color of soil and mulch, temperature, time of year, and the direction of prevailing winds create different microclimates on each aspect of a given landscape. Therefore, aspect may influence the choice of color and depth of mulch material to absorb or reflect heat, insulate, or determine the amount needed to resist blowing.

Slopes with southern and western exposures are considerably hotter and drier and have more variation in temperature than slopes with northern and eastern exposures. Temperatures are about 10 to 12 degrees higher on bare slopes with southern or western exposures than on slopes with northern or eastern exposure. Bottoms of north-facing slopes are cool and moist, whereas the top of south-facing slopes are warm and dry and are usually 5 to 10 degrees warmer than base.

During the period of highest temperature, soil temperatures on a southern exposure have been found to be 7 to 10 degrees lower under mulch than on a bare slope.

The slope direction affects the ease of vegetation establishment and stand survival. Some plant species are better adapted than others to specific aspects. For example, pine trees usually thrive better than most hardwoods on south slopes. Mulching provides a more favorable microclimate to help establish vegetation. It is usually more beneficial to seedling establishment on south and west aspects than on north and east ones.

Surface color of a minesoil and exposure is often a limiting factor for vegetation. Dark material on the surface absorbs large amounts of solar energy resulting in elevated surface temperatures lethal to seedlings. This may occur, especially during summer periods, on south and west exposures where high temperatures may cause soil to dry out more rapidly. In such instances, a light-colored mulch should be used to reflect radiation. Due to varying effects of mulches on temperature, it may be desirable to use different mulches at different times of year and on different slope aspects (see Mulch Application).

Roughness

Roughness of the surface has an effect on erosion by wind and water. A rough surface is better than a smooth one for controlling erosion and aids in adhering a mulch to a site. Certain mulch materials spread over a smooth, hard minesoil surface may be subject to slippage, washing, or blowing. Maintaining a rough surface will ameliorate this situation (see Mulch Application).

Soil Properties

Knowledge of soil properties is especially useful for identifying and treating those minesoils with properties that limit or prevent establishment and growth of vegetation. Such knowledge can be helpful in selecting organic mulch materials and plant species that are best suited or adapted to specific sites or conditions.

The most important problems threatening the physical integrity and ability of minesoil to support plant growth are erosion and overcompaction. Poor nutrient status and upward migration of toxic elements or salts present problems in some areas. An analysis and knowledge of the characteristics of the minesoil and overburden from the premine planning phase of the operation and of the regraded and topsoiled areas are necessary to indicate what conditions must be ameliorated on the site.

The type of spoil and soil materials on the site will affect the amount of erosion. Steep, bare, unvegetated minesoils are subject to high rates of erosion and soil losses can be significant. A vital objective of minesoil surfacing activity is reducing or preventing this erosion.

The inherent erodibility of soil is a complex property dependent upon its surface condition, structural stability, texture, organic matter content, moisture content, and infiltration capacity. Runoff and erosion vary from mine site to mine site depending upon these characteristics.

Minesoil

Surface mining disturbs the original soil profile creating spoil that is often called "minesoil". These materials are characterized by a wide spectrum of physical and chemical properties. In southern Appalachia, for example, the parent rock materials are generally sandstone, shale, and slate. Nonhomogeneity of spoil is the rule and must be contended with in any mulching operation. Moisture and temperature variances occur as a result of the heterogeneous nature of the spoil aggregate created during surface mining. On sandstone minesoil surfaces, crusting and moisture stress have resulted in poor germination and seedling development. Mulch applied at seeding has greatly increased germination and survival of herbaceous plants.

Minesoil is among the most hostile of environments for the establishment and growth of plants. It is usually low in nutrients, both the primary ones, such as nitrogen and phosphorus, and the minor ones. It may exhibit extreme droughtiness due to a lack of fine material and a predominance of rock fragments. Physical characteristics may be very poor because the soil is stony, has too much clay, is impermeable, or drains rapidly. The amounts of the different geologic materials and the manner in which they are handled and mixed during mining and grading directly affect the physical, chemical, biological, and mineralogical properties of minesoils. These properties and their relationships to each other determine, to a large extent, the success of plant growth and the benefits of mulches.

Physical Properties

Soil physical properties are important in determining the productivity of a soil. They influence the amount, distribution, and movement of water and air in the soil, temperature relationships, as well as soil chemical and microbiological properties.

Physical problems include extremes in texture, lack of favorable structure, lack of organic matter, and low inherent fertility and high erodibility potential. Treatment of physical problems can include mulching. Countering the adverse effects of poor texture, depth and structure, color, surface, roughness, and stability by mixing spoils and adding organic matter will improve soil aggregation. This influences the degree of compaction and crusting, plasticity, ease of root penetration, moisture infiltration, permeability, drainage, moisture holding capacity, temperature, evaporation, aeration, retention of plant nutrients, efficiency of tillage, and anchorage of plants.

The best solution to physical problems is to prevent them. A premining analysis of the overburden could be beneficial in determining how to separate or mix different rock materials during mining and grading so that the materials left on and near the surface will have acceptable physical properties. On some areas, replacing topsoil may improve the physical qualities of the reclaimed surface for plant growth. But in other situations, improper placement of topsoil may result in adverse qualities such as high bulk density.

Structure.--Soil structure is the aggregation of the primary soil particles into compound parts or clusters. Aggregation affects the extent of runoff and the movement and intake of water and air into and through the soil-surface zone. A highly granular soil ensures a more stable system of pores for absorbing moisture and air. A structureless soil becomes puddled and crusted, therefore compacted, and increases the danger of runoff and erosion. In mining, after backfilling and regrading, unless sufficient topsoil has been stockpiled and respread, the heterogeneous spoils possess little desirable physical structure.

Typically, fresh minesoils in Appalachia have low concentrations of organic matter and high percentages of coarse fragments with weakly developed structure. The surface horizon contains the greatest amount of fine material. Fine clay particles often create an almost air-tight crust and dry out rapidly after a rain and sometimes become very droughty during summer months.

Many organic compounds in mulches are capable of aiding in the formation of aggregates. As the mulch decomposes or is washed into the soil, the structure of the soil is gradually improved. The decomposing mulch materially increases granulation. This effect may be due to both the presence of rotting organic matter and to substances produced by soil organisms. During decomposition of the organic material, soil microorganisms produce or secrete gums, waxes, and other insoluble substances that coat and bond together the individual soil particles. Concentrations of these binders should be maintained. Higher concentrations of nonerodible soil aggregates and bonding substances are present in soil where organic mulches are present than in soil with no mulch. Humus has a high cation exchange capacity and as a result, a high ability to bond ions at exchange sites.

Organic mulch improves and stabilizes soil structure and tilth without cultivation. The mulch layer helps to prevent the surface soil from "running together" and crusting over. A friable crust is found under mulch, whereas a hard crust is dominant where no mulch exists. As the decaying organic matter works downward the soil becomes more friable and is better penetrated by water, and its aeration is improved, thus stimulating root and biological activity.

Texture.--Soil texture refers to the relative properties, of a particular soil, by weight of various sizes of sand, silt, and clay particles. These three factors combined form roughly 45 percent of an "ideal" soil. Sand particles are the largest, silts are intermediate, and clays are the finest.

The relative proportion and distribution of the various size particles and rock fragments affect water relations, soil structure, bulk density, erodibility, cation exchange capacity, and workability of the minesoil. Sand, when dominant, forms a coarse texture or "light" soil that allows water to infiltrate more rapidly but the soil dries out quickly. Silts and clays make up fine textured or "heavy" soils and can be plastic when wet and very hard when dry.

In minesoils with no adverse chemical characteristics, plant growth usually is most favored where about equal proportions of fine and coarse materials are present. Generally, minesoils that are high in silt, low in clay, and low in organic matter are the most erodible. The absence of a mulch or too low a mulch rate can have a negative effect on particle-size distribution. With little or no mulch or organic matter, contents of fine particles will decrease in the surface 0- to 1-1/4-inch layer due to raindrop impact and runoff.

Maintenance of a soil in a granular friable state is helped by the addition of an organic mulch, which can counteract the adverse effect of poor texture by improving drainage of heavy clay soils and water-holding capacity of sandy soils by enriching them with natural humus.

Bulk Density.--Bulk density is the weight of a unit volume of dry soil, ordinarily expressed as grams per cubic centimeter. Soils that are loose and porous have low bulk density; those that are densely structured or compacted, or high in clay content have high bulk density. The size and volume of pores are important to plant growth because they influence the movement of water and air in the soil. The bulk density of minesoils is related mostly to the types and amounts of the geologic and soil constituents and the proportions of different particle sizes. Excessive movement and compaction by grading and soil-moving equipment can also affect bulk density. Bulk densities of minesoils are usually greater than those of undisturbed soils because of their compacted state, lack of structure, immature pedogenetic nature, and high coarse-fragment content.

Surface mulches effectively decrease bulk density. The nature and extent of the physical effects vary somewhat with the amount and size of mulch particles. Coarse particles tend to decrease the water-holding capacity if incorporated into the soil. Very fine particles tend to puddle and exclude water and air from the soil. Bulk density decreases with increased mulch rate due to more organic matter and higher biological activity on properly mulched areas than on areas with little or no mulch.

Color.--The color of a soil is important in terms of the heat budget at the soil surface. Soils high in organic content and dark in color will absorb more energy than those light in color. Whether the higher heat absorption will result in a warmer soil depends on the amount of moisture. A dark-colored soil that is somewhat poorly drained may not warm up in the spring as quickly as a well-drained, light-colored soil.

Color can be a clue to chemical characteristics. For example, sandstone with a brown interior color is weathered and will not be toxic to plants. Sandstone with a gray interior is unweathered and may be toxic to plants because it may contain unoxidized pyrite. Black shales often are acid and toxic-forming and should be buried under nontoxic material. Occasionally, dark-colored materials are not acid and chemically are the best overburden material available for plant growth. In such instances the material should be left on the surface and mulched, or if possible, lightly covered or blended with topsoil or light-colored spoil material.

Soil Replacement.--Replacement of native soils on surface-mined areas may benefit or harm the establishment of vegetation. Few of the benefits and disadvantages are universal to all surface mines because native soils, as with minesoils, vary greatly from one region to another and among areas within regions. In some areas, such as northern Illinois, the native prairie soils are thick and relatively fertile. Where surface mined, many of these areas are regulated as prime farmlands under special provisions of the Federal Surface Mining Control and Reclamation Act of 1977. In other areas, such as in much of the Appalachian Region, native soils are thin, highly leached, and relatively infertile. Replacement of these soils may not always enhance the establishment and productivity of vegetation on mined areas.

The primary goal of replacing soil is the improvement of the quality of plant-growth medium on areas where the spoils or minesoils are chemically and physically less desirable than the native soils. Usually, soil replacement will create a fairly uniform surface condition over the entire area with few or no rocks to interfere with tillage, planting, and seeding. Perhaps the most universal benefit of soil replacement, especially of the surface or A horizon, is the potential source of soil fauna, microorganisms such as endomycorrhizal fungi, and seed, rhizomes, or other plant parts that will help reestablish the native vegetation. Immediate replacement of the soil is most beneficial because populations of many of the biological organisms are reduced by long-term storage or stockpiling of soil.

Detrimental effects of soil replacement can occur on areas where covering soils have chemical and physical properties that are less desirable than those of the spoils that will be covered. Often, the replaced soil will be compacted and physically degraded by repeated travel of the earth-moving equipment. Replacement soils often erode more easily than spoil materials. The interface between the replaced soil and the covered spoils sometimes creates a barrier to root penetration. Some replacement soils may contain seed of unwanted plant species that could produce competition with the desired planted species.

Chemical Properties

Chemical composition of the minesoil is strongly related to the geologic origin of the parent material. A soil developed in limestone will be characterized by high levels of calcium and perhaps magnesium. In Appalachia, the parent rock materials are predominantly sandstone, which contains various amounts of sulphur bearing pyritic shales that may cause high acidity in soils. The geologic materials that are exposed are often extremely infertile and may be highly toxic with accompanying high concentrations of salts, acids, and metals such as iron, aluminum, and manganese in mine-water drainage.

Plant growth is closely correlated with the chemical composition of the minesoil. The condition and inherently low nutritional levels of the minesoil may inhibit or completely prohibit plant life. A chemical laboratory analysis of the spoil will establish pH and toxic elements that have to be neutralized, and the nutrients needed for plant growth. After the composition of the spoil material has been determined, then amendments are selected to modify the spoil medium so that plants may prosper.

The chemical properties of minesoils most relevant to mulches and revegetation are chemical reaction (pH), acid and mulch induced toxicities, and nutrient availability.

Reaction.--Soil reaction is the degree or intensity of soil acidity or soil alkalinity expressed as pH. The pH scale ranges from 0 to 14. A pH of 7 is neutral: figures below this are increasingly acid and values above it are increasingly alkaline. The pH scale is logarithmic, that is, the intensity of acidity or alkalinity changes tenfold with each unit pH. For example, a pH of 4.0 is 10 times more acidic than a pH of 5.0, and a pH of 3.0 is 100 times more acidic than a pH of 5.0. The chemical elements in the soil eventually may be dissolved in or mixed with water to create soil conditions that are acid, neutral, or alkaline in reaction.

Soil reaction (pH) may be considered a symptom of the particular chemical condition that caused it, and hence, it may be used to indicate the possible effect of these conditions on plant growth. It is probably the most useful criteria for predicting the capacity of minesoil to support vegetation. A knowledge of the conditions that cause different soil reaction, therefore, is valuable in reclaiming and revegetating minesoils. Not only is plant growth affected by pH, but also inferences can be made about other qualities. For example, the availability of some plant nutrients is limited in both extremely acid and strongly alkaline soils, but these nutrients are available to plants in soils that are moderately acid to slightly alkaline.

There is a natural tendency for soils to become increasingly acid in humid climates because rainfall tends to leach away bases liberated by ionic exchange and mineral decomposition. In the humid section of the Eastern United States, minesoils are usually in the acid range (pH below 7.0), though some are mildly to moderately alkaline (pH 7.0 to 8.5). Most agricultural soils have a pH range of 5.0 to 8.5. Problems with revegetating the alkaline minesoils are few. Problems with revegetating acid minesoils are more common, especially those that are extremely acid (pH 4.0 and lower). Oxidation of iron sulfides found in the coal and overburden strata is the primary cause of extremely acid and toxic minesoils.

A pH reading also can indicate where an amendment is needed for neutralizing acidity. A recommended practice for treating acid minesoil is to raise the pH to 5.5 or higher by applying lime. At pH 5.5, most of the toxic elements will be precipitated from the soil solution and will no longer have harmful effects on plants. The application of certain fertilizers tends to increase soil acidity through the development of mineral acids.

Soil reaction generally follows the normal seasonal fluctuation with increased acidity in the summer months. This phenomenon may obscure soil reaction changes brought about by decomposition of mulch. Concentrations of various cations can be directly or indirectly affected by organic mulches. Soils mulched with large quantities of organic matter may release iron and manganese in concentrations that increase with ease of biodegradability, suggesting a biologically induced reaction. Mulch materials are usually basic and thus favorably increase pH in the soil surface.

The accepted method of salinity control is to provide sufficient and effective leaching and drainage. Salt concentrations in plant rooting zones can be decreased by surface applied mulches. Mulches help to reduce the amount of capillary movement of the soil solution to the surface (evaporation) and thereby prevent the concentration of soluble salts at the soil surface. In addition, mulch usually results in improved infiltration and percolation, thus, enhancing the leaching of salts.

The pH values that sometimes result from the addition of organic material may be a factor to be considered. If plants are known to be sensitive to soil reaction, the effect of organic material on the pH value of the soil should be ascertained before they are used. When acid material is applied to a plant that requires lime, it may be harmful if the soil is already near the lower limit of acidity tolerated by the plant.

Nutrients.--Chemical properties affect the amount and availability of plant nutrients in the soil. The sixteen elements needed for the growth of higher plants are commonly referred to as plant nutrients or essential elements.

Nitrogen, phosphorus, potassium, calcium, magnesium, and sulphur are required in large quantities and are referred to as the macro or major elements. Nutrients required in considerably smaller quantities are called the micro or trace elements and include manganese, iron, boron, zinc, copper, molybdenum, and chlorine.

The carbon, hydrogen, and oxygen combined in the photosynthetic process are obtained from air and water; the remaining 13 elements are obtained from the soil. Most of these nutrients exist in organic matter and in mineral form and as such are unavailable to plants. Nutrients become available through organic matter decomposition and mineral weathering. The nutrients are absorbed from the soil solution or from colloid surfaces as cations (+) and anions (-).

Through its decomposition, organic matter is a potential source of nitrogen, phosphorus, and sulfur. Usually, in the absence of fertilizers and mulches, the soil organic matter would supply the nitrogen and only a part of the phosphorus and sulfur that plants need. The balance of the nutrients is supplied through decomposition of inorganic or mineral particles of the soil. Mineral decomposition is extremely slow in comparison to the rate of decomposition of organic matter. A marked increase in soluble nitrogen, phosphorus, calcium, potassium, magnesium, and boron has been found under an organic mulch. Very few soils contain all of the necessary ingredients to support desirable vigorous plant growth, therefore, an initial and continuous supply of nutrients and organic materials must be provided.

Nutrient Deficiencies.--The minesoils of Appalachia are usually deficient in nitrogen, phosphorus, calcium, magnesium, and to a lesser extent, potassium.

In most instances nitrogen is deficient, especially where original topsoil and associated organic materials are of little or no consequence or were destroyed during clearing operations. Applications of supplementary nitrogen are necessary if successful herbaceous vegetation is to be established. With few exceptions, minesoils also need applications of phosphorus. However, potash is not usually needed. For most minesoils, it is recommended that 50 to 100 pounds of nitrogen and 50 to 100 pounds of phosphorus per acre or 150 to 300 pounds of ammonium nitrate (33 percent N) and 100 to 200 pounds of triple super phosphate (45 percent P) be added.

Plant-available potassium is adequate for plant establishment in most coal minesoils because clay, minerals, micas, and some feldspars that constitute a source of potassium usually are present in the overburden materials. Thus, use of potassium fertilizer usually is not needed for establishing vegetation. However, occasionally some spoils need potassium as part of the fertility program.

Deficiencies of other nutrients undoubtedly occur on some minesoils, but most of these have not yet been defined. It is known that on some minesoils, imbalances between calcium and magnesium occur that can hinder the establishment and vigorous growth of vegetation.

Chemical analyses of the spoil material or plant deficiency symptoms can indicate when elemental deficiencies exist. A nitrogen deficiency is shown by symptoms generalized over the whole plant; plant light green in color, lower leaves yellow. Likewise, a phosphorus deficiency is shown by dark green plant developing red and purple colors; lower leaves sometimes yellow, drying to greenish brown or black. A potassium deficiency is shown by localized symptoms; mottling or chlorosis on lower leaves; small spots of dead tissue usually at tip of leaf and between veins.

Generally, plant nutrient deficiencies become a major problem on most spoils, but instances occur in which certain nutrients from weathering rock are abundant.

Carbon-Nitrogen.--Applications of fresh organic materials that are high in cellulose often result in nitrogen deficiency due to microbial immobilization of soil nitrogen during decomposition. Nitrogen is tied up by cellulose decomposing organisms, especially during the early stages of the decomposition process. When the microorganisms cannot obtain enough nitrogen from the mulch itself, they turn to the soil for their nitrogen supply. If too much of the available nitrogen is immobilized by the microorganisms, plants will show typical signs of nitrogen deficiency. It has been found that nitrogen immobilization usually peaks at about 40 days, and can usually be overcome by applications of additional nitrogen along with other nutrients (chemical fertilizer) necessary to assure microbial activity and plant growth.

From the nutritional standpoint, the major shortcomings of various organic mulches are their high carbon to nitrogen (C to N) ratios and subsequent fixation of the inorganic nutrients. Carbon to nitrogen ratio is the relative proportion, by weight, of organic carbon to nitrogen. Most plant materials contain between 40 and 45 percent carbon, so the C to N ratio can be estimated if the nitrogen content of each material is known. The C to N ratios of plant materials vary widely. For example, wood wastes commonly have a ratio of 400 to 1, cereal straw 80 to 1, animal manures less than 30 to 1, and young clover 10 to 1.

Plant materials with small C to N ratios (25:1) are relatively rich in nitrogen, whereas those with higher values (200:1) are relatively low in nitrogen. Organic residues with ratio less than 15 to 1 or 20 to 1 usually contain enough nitrogen to satisfy the requirements of the decomposing organisms. The ideal ratios for C to N is from 20 to 1 to 25 to 1. Organic residues do not begin to release nitrogen until their C to N ratio has been narrowed to 15 to 1 or their total nitrogen content is 1.7 percent. Carbon to nitrogen ratios greater than 25 to 1 can cause nitrogen deficiency because the microorganisms that attack the organic mulch are more efficient than plants in using what organic nitrogen there is in the soil.

Because of their high C to N ratio, most organic mulches need additional fertilizer to compensate for the microbial tie-up of nitrogen during the decomposition process. The quantity of nitrogen required is a function of mulch particle size and the soil surface area that is in direct contact with the mulch material. The microbial immobilization rates of a variety of organic materials range from 0.2 to 1.7 percent of material weight. A minimum amount of nitrogen is needed to sustain microorganisms that are active along the mulch and soil interface. Sufficient nitrogen should be added to the material to bring the nitrogen concentration of the mass up to 1.2 to 1.5 percent. This corresponds to about 115 pounds of ammonium sulphate or 72 pounds of ammonium nitrate per ton of dry mulch. Nitrogen reserves will not be overtaxed if the preceding fertilization practices are followed.

Composting organic materials decreases the C to N ratio and increases the base exchange capacity of the material, while also increasing the content of essential nitrogen, phosphorus, potassium, calcium, and manganese. The chemically treated material can be inoculated with Corprinus ephenerus, an organism that is efficient in decomposition of cellulose. Chemical treatment includes addition of anhydrous ammonia, neutralization with phosphoric acid, and enrichment with other essential nutrients.

Toxic Substances.--Substances toxic to plants and to certain microorganisms accumulate in some soils as a result of the incomplete decomposition of organic matter. Methane, hydrogen sulfide, phosphine, skatole, indole, and numerous organic acids are toxic compounds produced, but they are generally considered merely products of improper soil management. If good drainage and tillage are provided with the proper use of fertilizer and lime, these toxins should not be a problem.

The phytotoxic compounds isolated from fresh and decomposing organic mulches include organic acids, lactones, tanins, phenols, alkaloids, and turpenoid compounds. Presumably, for a compound to affect vegetative growth, it must be adequately water soluble or have a vapor pressure high enough to diffuse the plant. Phytotoxins may be present in certain crop residues or may be produced by microbiological degradation of the residues.

Occasionally, some wood or bark contains small amounts of toxic compounds that may be harmful to germination of some seeds and early growth of certain plants. Growth inhibiting compounds found in wood are phenols and phenolic compounds, turpenes, steroids, alkaloids, cyanids, organic acids, and bark extract. Certain phenolic compounds may retard or inhibit enzyme activity. Bark tannin in particular concentrations may kill certain plant pathogenic fungi.

Certain wood constituents especially turpentine, resins, oils, and tannins, when present in large amounts, may exert a toxic action on plants either directly or through their decomposition products. In some instances, the temporary growth-depressing effect of C to N ratio may be amplified by tannin and other organic-solubles present in certain types of wood.

Concern that wood residues contain toxic components harmful to vegetation may be over emphasized. Most woods and barks are not appreciably toxic to plants and can be used safely as mulches if adequate nutrients are supplied and the soil is not too acid.

Soil Organisms

Although soil organisms comprise only a small fraction of the soil mass, they play a vital role in the development and maintenance of vegetation and in the establishment of natural ecosystems. A teaspoon of soil may contain billions of living organisms that depend on plant and animal residues (organic materials) and soil oxygen to carry on their life processes during which important chemical elements are released and are made available for plant growth. The vast number of soil organisms are grouped into flora (plants) and fauna (animals).

Soil Flora.--The more important groups of plant organisms found in minesoils are bacteria, fungi, actinomycetes, and algae. All of the groups aid in the decomposition of organic matter and plant residues and the nitrification or accumulation of nitrates in the soil as a result of the decomposition process. Bacteria are the most numerous and are important in organic matter breakdown, nitrogen and sulphur transformation, and nitrogen fixation.

The biological processes involving decomposition, nitrogen fixation, and nitrification are favored by pH values in the neutral range. The activity of bacteria and actinomycetes is significantly reduced at a pH of 5, while fungi dominate under these conditions due to their tolerance to acidity. The kinds and numbers of organisms in recently mined and unvegetated minesoils are very few or completely lacking as compared to agricultural and forest soils. However, when an area is mulched and as the vegetation becomes established the populations of some of these organisms will increase by natural processes. Other types may need to be artificially introduced. Some plant organisms are symbiotic, which means that they give to and derive benefit from the plants on which they live. For example, Rhizobium bacteria live on the roots of legumes and take nitrogen from the air and fix it in nodules for use by the host plant. Similarly, most species of plants have mycorrhizal associations that involve root-inhabiting fungi that tend to increase the plant's ability to take up nutrients, especially phosphorus. Mycorrhizal associations are beneficial to survival and growth of most plants.

Mulching benefits the "life" of the soil. Generally, higher moisture conditions and lower temperatures under a mulch favor soil organisms. Woody mulches promote higher populations of organisms, especially molds. Wood mulches are strongly acid (4.5) which in part accounts for the high mold count.

Soil Fauna.--The animal organisms are the worms, beetles, bugs, and similar creatures that are primarily responsible for consuming and altering organic materials and burying or mixing them in the soil. Many new minesoils normally are devoid of soil fauna. Natural establishment of soil fauna populations is relatively slow because most soil fauna are not highly mobile. Thus, several years may be required for a mined area to be repopulated by the natural movement of organisms from adjacent undisturbed lands. Artificial introduction of animal organisms is possible and has proven beneficial in small experimental plots, but its practicality has not been demonstrated on large areas. Immediate replacement of topsoil is probably the most promising means of establishing soil fauna on mined sites.

Pathogen.--There has been some concern about using trimmings of trees that are diseased or infected with insects. If the trimmings are composted for 2 to 3 months, any problem is usually eliminated.

Organic Matter

Organic matter is plant and animal residue in various stages of decomposition. The organic matter is important in the surface environment of the soil because it affects soil physical, chemical, and biological properties. The organic matter in soil is one of the most important and, also, one of the most easily exhausted resources.

The relative amount of organic matter in soils is generally recognized through color. Dark soils are usually considered superior in organic matter content to lighter soils. The base exchange capacity and erodibility of soil are largely dependent upon organic-matter. As the amount of organic matter increases, the ability of the soil to absorb water increases and runoff is reduced, thus, minimizing erosion. The ideal amount of organic matter in soil is about 5 percent. Most minesoils are inadequately supplied averaging less than 1 percent.

Amending minesoils with organic matter may not be practical; however, normal applications of organic mulches contribute to the establishment of an initial supply of organic matter to the soil. The gains in organic matter in the surface inch are directly related to the use of mulch and the nature and abundance of vegetation. The bulk of the organic matter added to the minesoil comes through topsoil replacement and use of a mulch. Organic matter is important to the rooting zone because it supplies nitrogen (soil organic matter is about 5 percent N), helps develop a more stable soil structure, and holds water and nutrients.

The composition of organic residues is important to the nature and rapidity of the liberation of the nutrient elements in forms available for plant growth, and to the formation and nature of the residual organic matter. Lignin, which occurs in older stems and other woody tissue, occupies an important place in the formation of humus making up 40 to 45 percent of the total. Because lignin content of wood by-products is higher than that of crop residues (4 to 12 percent), it generally results in greater increase in stable soil organic-matter content and is very resistant to decomposition.

Major components of wood as percentages of total dry weight are:

<u>Component</u>	<u>Softwood</u>	<u>Hardwood</u>
	<u>-----Percent-----</u>	
Cellulose	10 - 42	42 - 51
Lignin	27 - 33	19 - 24
Hemicellulose	23 - 31	23 - 38

Oat straw decomposes fairly rapidly. More than 50 percent of the hemicellulose and 10 percent of the cellulose will be decomposed within 10 days after application.

Because the decomposition of organic matter is a biochemical process, any factor that affects the activities of the soil organisms will affect the rate of organic-matter decay. The C to N ratio of the waste material often dictates the rate and extent of decomposition.

In general, the younger the plant from which organic material was obtained the more rapid will be its rate of decomposition. This occurs because of the higher content of water-soluble constituents, a higher nitrogen content, a more narrow C to N ratio, and a smaller percentage of lignin. Of the various plant residues, those having the higher nitrogen content usually decompose most rapidly. Maintenance of organic matter is a problem in soils of a sandy nature in warm humid regions.

Organic matter is particularly important in clay, sandy, saline, and alkaline soils. The bacterial decomposition of organic matter in such soils increases the ability of the soil to buffer rapid changes in alkalinity and acidity and to neutralize some potentially toxic substances.

Moisture Relationships

Moisture is a major factor in reclamation and vegetative establishment. Soils that are able to hold large quantities of water are desirable.

The water-holding capacity of a mine soil depends on its texture, permeability, depth, and organic-matter content. Moisture is lost by runoff, plant transpiration, soil-surface evaporation, and percolation through the soil.

Infiltration is the process whereby water enters the soil surface. Under most conditions, the movement of water through a soil is a relatively slow process. As a result, many storms supply water at a faster rate than most soils can absorb it. When the rainfall rate exceeds the infiltration rate, water runs over the surface and erosion may occur.

A mulch cover can be used to protect the surface from forceful contact of raindrops and to slow the movement of surface water allowing additional time for infiltration. A desirable soil profile acts as a sponge that retains water near the surface. When mulch is added, the soil surface becomes porous and remains loose and friable. The soil surface is protected from sealing and "running together" or crusting over due to raindrop impact, and, as a result, higher infiltration rates are maintained.

The effectiveness of mulch in maintaining high infiltration is correlated with the type and percent of surface cover. Coarse textural materials will decrease surface runoff. Large particles usually absorb less moisture than fine materials. However, coarse materials with a high percentage of fines can have a wicking action that draws moisture out of the soil and later loses it through evaporation. Some fine-textured materials have been known to crust over and shed water and may be of little value in soil-plant-moisture relations.

Mulched surfaces generally have a high rate of water intake compared to bare surfaces for all periods of rainfall. The nature of the rainfall pattern and time lapse between rains has considerable bearing on the effectiveness of mulch in conserving water.

Mulches have been shown to conserve substantial moisture to a depth of about 12 inches. Any thickness of organic mulch will increase soil moisture. However, optimal application depth for moisture modification has not yet been determined.

Evapotranspiration causes most of the water removal from soils under normal field conditions. It can account for the loss of 30 to 40 inches of water during the growing season for a stand such as alfalfa.

After water enters the soil, some of it is normally drawn back to the surface through capillarity and is lost by evaporation. Evaporation from soil surfaces can be modified and influenced by using organic mulches. In situations where the soil surface is exposed to the sun, a 2-inch layer of mulch can cut water loss due to evaporation by as much as 50 percent.

Mulch acts as a one-way valve, allowing water to enter the soil but reducing evaporation later. When the air becomes dry and has the capacity to absorb water from a wet surface, then mulches generally dry quickly. When dry, they no longer act as capillary conduction and further drying of the soil profile is slowed.

Relative humidity and temperature play a major role in determining how quickly water is lost and consequently in determining the amount of water that plants need. In certain areas, it is believed that warm moist air invades the interior of the porous mulch and moisture condenses when the air comes in contact with cooler soil surface.

A mulch should not have a high absorptive capacity itself because during periods of light rain or long intervals between rain very little water may actually reach the soil. Certain kinds of mulches (peat, sawdust) intercept and absorb a large share of the rainfall, resulting in less water available for plant growth.

Climatic Variables

An understanding of how climate influences the interaction of physical, chemical, and biological processes is essential to the successful reclamation of mined lands. Climatic conditions in a given area are governed by such factors as latitude, elevation, prevailing winds, moisture source, and terrain. Local climatic information may be obtained from the Soil Conservation Service or the U.S. Department of Commerce.

Knowledge of the effects various mulch materials have on climatic conditions is helpful in determining how and when each type of mulch can be used to best advantage in land reclamation. Mulch materials should be selected for their adaptability in meeting the macroclimatic and microclimatic conditions found at the site.

Seasonal Characteristics

Elevation affects length of growing season. Generally, as elevation increases length of growing season decreases. In high-elevation areas, mulches can reduce the problem of frost heaving and its adverse effect on young seedlings.

Mulch color can help raise spring temperature and speed up the germination rate, or can help lower summer temperatures, thus aiding areas where the soil surface is affected by solar radiation (see Mulch Application).

Precipitation

Precipitation and its associated potential runoff are important elements that affect the ability of a mulch to remain in place and to control erosion. Mulch must be adapted to expected rates and kinds, seasonal distribution, frequency, duration, volume, and intensity of precipitation.

Regions with a large annual rainfall are subject to severe erosion. The coal regions of the humid East have an annual precipitation of about 33 inches or more (Fig. 7).

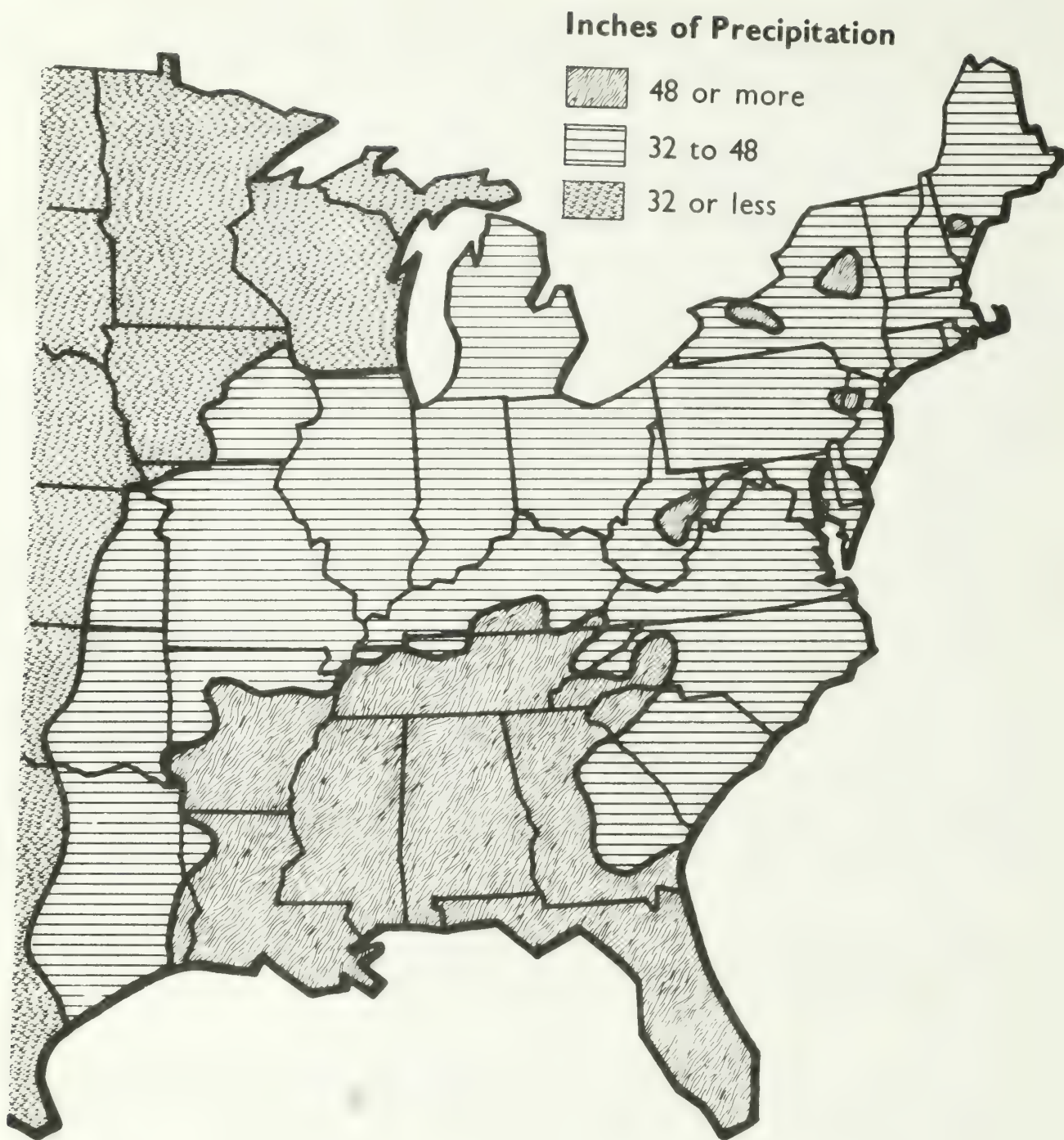


Figure 7.--Precipitation zones of the Eastern United States.

Rainfall energy is a better prediction of erosion than rainfall amount. The erosiveness of flowing water depends on its velocity, turbulence, the amount and type of abrasive material it transports, and concentration of runoff in rills and channels.

Mulching is particularly valuable in protecting areas from high-intensity short-duration storms by dissipating kinetic energy of raindrops, lessening splash erosion and surface sealing, lessening rill and channel erosion, and allowing more infiltration. Mulch can cut water losses by two-thirds and soil losses by as much as 80 percent.

Temperature

The temperature regime and the microclimate at and near the soil surface have a significant effect on the reclamation process. Plant growth and microbial action are influenced by soil temperature. As temperatures decrease, the life processes of both plants and animals are slowed down. There is relatively little biological activity below 32°F or above 122 to 140°F for active shoot tissues. Leaf functions are impaired at temperatures over 107°F. Growth processes of most plants are sluggish at temperatures below 40°F. The most favorable limits are 70 to 90°F with 86°F the optimum temperature for absorption by roots. When soil temperature is high, roots stop growing and plants suffer even if moisture is plentiful. Temperatures in the root zone (3 to 12 inches) of drastically disturbed soils frequently exceed the lethal plant-tissue temperature of 120°F. The chemical processes and activities of soil organisms, which convert organic matter into available nutrients, are also materially influenced by temperature.

At any particular latitude the slope of the surface and its aspect will determine the amount of solar radiation reaching the soil surface. The angle at which radiation hits the surface influences the intensity of radiation. In the northern hemisphere soils located on southern slopes warm up more rapidly than those located on the level or on northern slopes. Maximum radiation intensity occurs on flatter slopes in summer when the sun is high and on steeper slopes facing the sun in winter when the sun is low.

Soil temperature is controlled or modified by regulating the incoming or outgoing energy or altering the thermal properties of the ground. One way of doing this is to place an insulating layer, such as an organic mulch, on the ground surface. The thermal properties of the ground can be modified by regulating evaporation, soil moisture content, and by mulch on the ground surface.

Organic mulches have a complex influence on soil temperature which varies with the mulch color, season of the year, and prevailing weather conditions. Mulch is used to mitigate the effect of solar radiation and drying winds and to provide proper soil temperature by decreasing evaporation and moderating extremes of diurnal and seasonal fluctuation. The color and type of material affect temperatures by absorbing or reflecting energy and by insulating the soil.

The daily air temperature in temperate regions reaches a maximum at about 2 p.m. The surface soil, however, does not reach its maximum until later in the afternoon. This lag is greater and the temperature change is less as depth increases. Clear weather accounts for rapid changes in surface soil temperature, and rapid movement of air above the soil accounts for a great loss of energy.

Usually, temperature changes lag in soils under a mulch because of the insulating effect. On a 24-hour basis, a mulch will result in greater soil-surface temperature variation but less variation within the minesoil body proper. Compared to bare soil, mulched areas have lower and more uniform soil-surface temperatures. In the summer, the average soil temperature of a mulched area will usually be cooler by day and warmer at night than bare soil. However, when temperature of bare soil approaches or falls below 32°F, the temperature effect is reversed.

In general, mulches applied at depths of 1/2 to 1 inch will decrease the range of surface temperatures. However, as the applications are increased to 2 to 4 inches the decrease becomes less significant.

Soil temperature of 108°F at a 2 inch depth and 100°F at a 4 inch depth are root-killing temperatures. In general, 3 inches of mulch will reduce the temperature by 8 to 10°F. This means that when the soil surface on bare ground is 108°F the temperature of soil under 3 inches of mulch would be 98°F at 2 inches deep and 90°F at 4 inches. Temperature drops an average of about 4°F per inch of soil depth.

Mulch Characteristics

In selecting an effective mulch for a specific reclamation job, consider: availability; physical, chemical, and biological properties of both mulch and minesoil; application procedures; overall application and maintenance costs; effects on vegetative response; and personal bias. To select the best material the basic characteristics of all available materials must be evaluated.

Availability

Once the type of mulch material has been selected, determine where it can be obtained, how it will be transported and applied, and how or where it can be temporarily stored until applied. These decisions should be made as early as possible because some materials may be difficult to obtain and others may be available only in a particular season.

Sources of materials should generally be available in all eastern states. Supplies should be locally available on or near the reclamation site in sufficient quantities, and preferably obtainable all year. Products should be nonhazardous; economical; and easy to handle, transport, and store.

Some residue materials such as bark often can be obtained at little or no cost, but handling, transportation, or application may require costly or specialized equipment. Sometimes an alternative mulching material is available but is not used because of lack of knowledge and uncertainty of its value. For example, some people believe that wood chips are acid-producing and toxic to vegetation.

Physical Properties

The physical properties most relevant to the selection of organic materials are: form, size, weight, color, and durability. Form, particle size, and weight determine whether the material will blow or wash away. In general, mulches with the longest fiber are the best for adhering to a slope. Large, coarse-textured, solid particles increase the size of pore spaces, while small, fine-textured particles tend to pack and bind which restricts air and water movement into and through the soil. A mixture with a range of particle sizes is desirable. The color and type of material can affect temperatures by absorbing or reflecting radiant energy. A durable material has tenacity and stringiness (like fiber), and should stay in place by becoming attached to the soil. Consider the potential for fire hazard when choosing materials.

Chemical Properties

Chemical properties to consider are: reaction, C to N ratio, toxicity, nutrient content, and durability. Reaction of minesoils should not be adversely affected by the mulch. Materials should be nontoxic to plants and microorganisms. Depletion of available plant nutrients during decomposition should be minimal.

Biological Properties

Where possible, the material should inoculate microorganisms into the minesoils. The decomposition rate should be slow enough to allow vegetation to become suitably established. Decomposition is usually more rapid in fine-textured materials such as sawdust or hydromulch, than in high-cellulose materials, such as straw and wood chips. Leguminous fiber mulches decompose at a faster rate than cereal fibers.

Measurement

The units of measure used for mulch applications are expressed as weight or volume per acre depending upon the type of mulch selected. Application rates relating to weight must be based on air-dry weight to assure uniformity.

Application rates of crop residues and solid animal wastes are generally given in tons per acre. For example, for unweathered straw and hay, the average is 1-1/2 to 2 tons per acre and for manure, 10 tons per acre.

Logging and wood manufacturing wastes are applied by the cubic yard because of the extreme variability in moisture content, which affects a weight basis. Municipal, industrial, and animal waste-water slurries or liquids and hydromulch are applied by the gallon.

Maintenance

Of paramount importance, is that the material selected has a low-maintenance character because periodic post-mining treatments after application can be costly. The ideal low-maintenance material would be resistant to washing, blowing, decomposition, and require no refertilization.

Vegetation Establishment

Basically, the growth of plants depends on the minesoil for the prime source of water, oxygen, and nutrients. Beyond this, the minesoil must provide mechanical support for the plant and an environment in which roots can function. Oxygen must be available for root respiration, and the carbon dioxide produced must diffuse out of the soil. Inhibiting factors such as acid and toxic forming materials, high concentrations of soluble salts, and high C to N ratios should not be present.

The growth of plants is the manifestation of many chemical and physical processes. Water plays a major role as a medium for these processes. Plant growth depends on temperature and proceeds properly if there is adequate heat in the environment. The amount of heat and water needed for optimum plant development covers a fairly wide range, but excesses or shortages of either can have a limiting effect on growth.

Harsh microclimates are often detrimental to the establishment of vegetative cover on surface-mined lands. Extreme diurnal surface temperatures and low moisture contents are the factors most detrimental to seed and seedlings. These problems make it difficult to establish and maintain a diverse vegetative cover that will meet the little or no maintenance requirements for reclaimed areas as set forth by PL 95-87.

Successful first-effort establishment of vegetation is economically important. Careful adherence to recommended seeding and planting techniques, procedures, and use of appropriate amendments and mulches greatly improve the chances for success.

The plant-growth environment is nearly always improved with mulch. Organic mulch provides microorganisms, organic matter, and some nutrients to the soil. Mulch holds seeds in place and provides maximum protection from erosion, predation, rapid temperature changes, direct sunlight, and loss of moisture during and after the germination period and until the new seedlings are sufficiently established. Woody seedlings that are heavily mulched benefit by root protection and reduced competition from excessive growth of unwanted vegetation.

Mulch selection and application rate need to be coordinated with vegetation species to be used. For example, Kentucky-31 tall fescue is suited for areas in which fertility is low and moisture is limited periodically during the growing season. The application rate of mulch could be reduced for these species whereas with others it may need to be increased. Mulch must encourage both a prompt vegetative cover and recovery of productivity levels that are compatible with the approved post-mining land use. The long-term purpose for mulching is to enhance and promote the establishment and development of a permanent vegetative cover.

Mulching nearly always shortens the time needed to establish a plant cover. It permits the use of lower seeding rates and improves environmental conditions for better germination, emergence, root growth, more efficient uptake of water and nutrients, uniform vigorous stands, higher yields, better survival, and better growth. Mulch reduces soil crusting and produces a more favorable seedbed for seedling emergence and conserves water in the rooting zone. Some mulches contain essential elements to aid plant growth. Mulch temporarily stabilizes disturbed soil while vegetation is being established.

Grasses, legumes, and woody plants respond to different soil mulching agents with native species having the highest potential for success. Because mulches greatly modify microclimates, species best suited to such modification should perform best. For example, greater total ground cover responses are often observed in legumes than grasses following mulch application of bark or wood chips. Also, some grass species may perform better under fiber mulches, such as hay, than under other types of mulch.

Wood residues may not be as good as crop residues for establishing Ky-31 fescue or orchardgrass. Very favorable germination and seedling growth of legumes is achieved under wood residue mulch. Seedlings of legumes such as crownvetch normally grow more slowly during the seedling year than vigorous grasses such as Ky-31 fescue and lovegrass. Also, seedlings of species such as crownvetch have been more successful where a mulch was used. Greater response may be noted in plant species that have a relatively low salt tolerance following mulch application, because increased moisture conditions under mulches may enhance leaching of salts from the plant rooting zone.

Germination

Microclimatic conditions are extremely important during the period of germination and seedling development on newly planted areas. At this time, plants must be supplied with adequate water and oxygen, and the temperature must be within the range necessary for germination and growth. During the several weeks following germination, the seedling produces rudimentary root systems and a primary leaf. The newly formed seedling cannot tolerate a dry environment for long.

Mulches are effective in protecting the newly seeded area from erosion and in enhancing seedling success. They have greatly increased germination and survival resulting in quick sod establishment in areas of high soil temperature and moisture stress. The effectiveness and suitability of mulch treatments are evaluated by the protection it provides from time of seeding until a stable size and density of vegetative cover is established.

Because of size and weight and depth of application, some mulches inhibit seedling emergence. Mulch depths of 2 or more inches will retard the establishment of most grasses and legumes (see Mulch Application).

Favorable vegetative response following addition of surface mulches is primarily related to regulation of soil temperature and conservation of soil moisture. However, mulches can cause slow germination and plant growth by lowering soil temperature. Increased mulch rates in the spring may delay the time that soil would reach favorable temperatures for seed germination. Also, light-colored mulches can be a disadvantage because they keep soils cool. Application of dark mulch can advance growth of plants by a month or more by increasing the temperature. Dark-colored mulches might have an advantage for fall seedings because elevated temperatures during suboptimum temperature periods might augment germination and growth.

Although reduced soil temperature, as well as reduced fluctuation of temperatures, beneath mulch is a possible benefit to growth, the most important benefits of mulching are reduced evaporation, increased infiltration rates, and greater retention of soil moisture.

In the humid region, mulched and fertilized vegetation is more drought resistant due to increased top and root growth and root penetration. The total water consumed may be greater, but it is used more efficiently.

Mulch on dry sites may be detrimental because seed can be fooled into germinating with the first light rainfall. This can encourage plant suicide because organic mulch can take moisture away from seed resulting in some dieback from lack of sufficient moisture for continued growth.

Undesirable Plant Growth

Presence of undesirable seed in some crop-residue mulches can affect reclamation. When straw contains seed heads, a volunteer start of grain may result. This may be advantageous as a nurse crop if the start is not too thick. However, seed that has been threshed from grain straw can produce vegetation that inhibits establishment of the seeded plant species. Aggressive plants of volunteer weeds or cereal grain in the straw crowd out the slow growing perennial grasses and legumes.

Oats straw contains many viable seeds that germinate and provide competition for the grass and legume seeding. Straw can be expected to contain 0.5 to 5 percent cereal seed by weight. This may result in considerable plant cover in the first year. One-fifth (20 percent) of the plants found on straw-mulched areas were nonseeded annuals that do not contribute toward long-term erosion control. Thirteen percent were weed species and 6 to 7 percent were volunteer oats.

Annual plants will develop early and provide additional erosion protection for the short term but offer little protection for the long term. They are prohibitively competitive with the planted mixture. Rice straw, if available, is better because neither the rice nor associated weeds are expected to grow on most unirrigated disturbed lands.

Manure that is high in bedding material may contain undigested seeds that could infest the land with weeds. Grain and hay seedlings generally emerge easily through the mantle of manure.

The use of hay as mulch may sometimes be restricted due to contamination with noxious weed seeds or with organisms that cause diseases in agricultural crops. Aggressive weeds may crowd the desired plants.

Hay is sometimes preferred as a mulch where vegetation is for land uses, such as wildlife habitat, because it may contain seed of species favorable to wildlife. Because of the seeds contained in hay, it may promote better grass cover than that of straw. Some hay may contain sufficient grass seed so that the hay serves both as a mulch and a seed source.

Wood residues, and municipal and industrial wastes usually eliminate introduction of undesirable species. Weed species, including the noxious varieties, are far less prevalent on bark-mulched areas than on straw- and hay-mulched areas. Coarse-textured mulch may trap airborne seed that will germinate and grow, but this is not a serious problem. Weed seeds do not germinate readily under a heavy mulch.

Herbicides, when incorporated with organic mulches, provide a synergistic effect. Herbicide and mulch combinations provide more effective control than when either is applied alone. The organic mulch holds the herbicide and provides a long residual life and reduces the chance of herbicide runoff and phytotoxicity to the treated plants. A secondary benefit is that small quantities of herbicide can be premixed and applied with mulch. Potentially, bark should be an excellent carrier for herbicide compounds.

Dichlobenil, diphenomil, and simazine products have been tested. The addition of herbicide to 2-inch oak bark mulch enhanced its weed-control properties. The herbicide killed the germinating weeds at time of mulch application. This virtually eliminated weeds at the start. Further weed germination and growth is reduced by the residual action of the herbicide.

Some plant species can be troublesome where planted in association with plants for other land uses. For example, Japanese honeysuckle is a valuable plant for wildlife cover and food. Yet, this plant can become a pest because it will rapidly spread and smother or suppress other plants growing near it. Planting of Japanese honeysuckle and other plants such as Kudzu and multiflora rose in conjunction with forestry or agricultural uses is not recommended. Authorities have classified some of the plants as noxious weeds and made it unlawful to plant them in certain areas.

Considerations When Selecting a Mulch

The following items should be considered when selecting a mulch to facilitate reclamation:

A. General Information

1. Distance of land application site from mulch source
2. Distance of land application site from waterways, urban areas, or residences
3. Proposed land use
4. Proposed vegetative species
5. Regional land use planning requirements
6. Expansion potential (additional land)

B. Environmental Interactions

1. Climate
 - a. Seasonal characteristics
 - b. Precipitation
 - c. Temperature
 - d. Prevailing wind direction
 - e. Evapotranspiration
2. Topographic and geologic features
 - a. Slope steepness
 - b. Slope length
 - c. Slope aspect
 - d. Erosion potential
 - e. Flood potential

- f. Infiltration and percolation characteristics
- g. Minesoil characteristics
- h. Ground water pollution potential

C. Land Use History

- 1. Crop
- 2. Pastureland
- 3. Forestry
- 4. Wildlife
- 5. Conservation practices
- 6. Irrigation potential

D. Application

- 1. Intended Use
- 2. Mulch depth
- 3. Mulch rate
- 4. Method of Application
- 5. Anchoring

Mulch Descriptions

Detailed information has been prepared for materials that are most frequently used and recommended and for some that have been successful on experimental plots but otherwise have been little used. The material descriptions are arranged by residue type:

Agricultural Residues

Straw
Hay
Manure

Silvicultural Residues

Bark
Hardwood
Softwood
Wood Chips
Hardwood
Softwood
Sawdust
Leaves

Municipal Wastes

Solid Wastes
Wastewater Sludge

Industrial Wastes

Wood Cellulose Fiber

Straw

Type of material: Long fiber cellulose

Sources: Cereal crop residue (wheat, oats, barley, etc.)

Packaging: Loose or baled (rectangular or round)

Availability: Local farms, farm stores (grain and feed), prior reclaimed land

Measurement: Tons, pounds

Properties:

Form: Fiber

Size: Minimum length, 6 inches; average, 10 inches

Color: Light yellow

Durability: One growing season

pH: 5.6 to 7.1

C to N ratio: Wheat 128:1 to 150:1; oats 48:1

Nutrients: lb/ton, dry matter

	<u>N</u>	<u>P</u>	<u>K</u>
Oats	12	4	30
Wheat	14	3	23

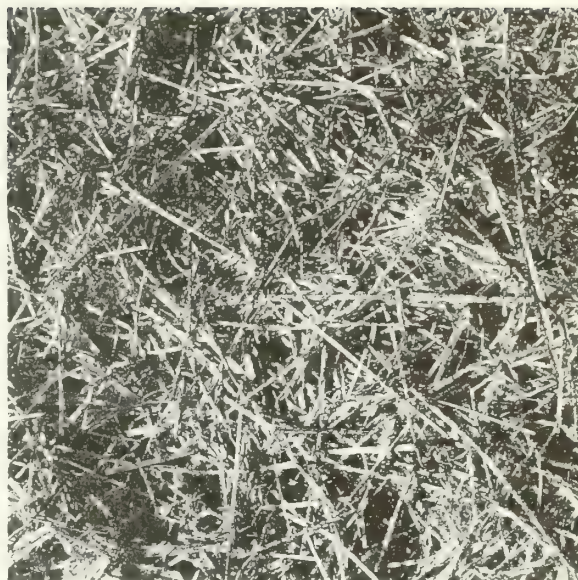
Application:

Intended use: Tons needed per acre - Seed cover: 1.5 to 2, Erosion control: 3,
Plant mulch: 4

Methods:

Application: Manual, spreader, or blower

Anchoring: Crimper or asphalt tackifier



Vegetative response: Weeds or grain seeds that are usually present can restrict desirable plant species. There is no long-term effect due to nitrogen deficiency.

Comments: Straw is one of the most economical mulches. However, cost is influenced by weather and demand. Supply can be undependable due to short-stem small grains and increased demand. Grain crops raised on previously reclaimed mine sites are a potential source. Usually 100 pounds of straw are produced for each bushel of wheat harvested. A grain yield of 40 bushels per acre would result in a straw residue of about 2 tons per acre.

Straw is available in 70 to 90 pound rectangular bales with 25 to 30 bales per 1 ton. Generally, unweathered, unchopped small-grain wheat, oat, or barley straw is best. Wheat straw is preferred because it does not decompose as rapidly as oat straw. Barley straw has a dusty character but is highly efficient. Compared to wheat straw, barley straw has a thinner stem shell, which makes it lighter in weight, and provides more coverage when applied by weight.

Dry straw usually contains about 15 percent moisture, 5 percent ash, and 80 percent organic matter. It will absorb considerable liquid (twice its weight) and can "wick out" moisture from soils. Rapid decomposition reduces its efficiency in retarding surface runoff. Straw improves soil aggregation and has no measurable effect upon soil reaction. Fats, waxes, and oils serve as soil aggregate binders and make up 1.5 percent of average wheat straw.

Straw obstructs solar radiation. One ton per acre can reduce soil-surface temperature by 10 to 15°F. In the spring, it can be a disadvantage due to its light color and reflective qualities, which slows warming of the ground and delays seed germination and early crop growth.

Straw materially reduces the formation of nitrates because of the soluble organic derivatives leached into the soil during decomposition. Microbial immobilization of nitrogen during decomposition averages about 1.5 percent of the original straw weight. Therefore, 1.25 to 1.5 percent nitrogen (50 to 60 pounds per acre) is needed with optimum mulch application (1 1/2 to 2 tons per acre). The anaerobic decomposition of wheat straw by a suspension of soil microorganisms has led to production of substances inhibitory to plant growth. Acetic acid was the phytotoxin present in greatest amount.

Straw is superior to manufactured short-fibered wood cellulose for soil protection. For optimum protection, it should be applied at the rate of at least 1-1/2 tons per acre or about 1 inch in depth. It should be spread 3 to 5 intermeshed straws deep. A 1-to 2-inch matt equals 125 pounds per 1,000 square feet or 2.7 tons per acre. Where straw makes extensive contact with the soil surface, its long fiber tends to block the path of the runoff flow and physically blocks the movement of soil particles. Much of this effectiveness is lost if the straw becomes perched or bridged above the surface. On 1:1 slopes subject to heavy rainfall, straw is difficult to hold in place and tends to flow down the slope. On a 3:1 slope, 2 tons per acre anchored with 400 gallons of asphalt emulsion can be effective in controlling erosion.

Application of 1,500 pounds per acre is about the least amount of straw that controls evaporation from the soil. When compared to bare soil, a mat 1-1/2 inches thick (about 2.25 tons per acre) reduced moisture loss by 73 percent. One-half ton per acre reduced soil loss by 66 percent; four tons reduced soil loss by 95 percent. A good treatment for erosion is a combination of 3,000 pounds per acre of straw mulch that is oversprayed with 700 pounds of hydromulch. Thick applications can create problems in the summer if the fibers thatch together preventing penetration of water. Also, thick applications can be a fire hazard when dry.

A fine-stemmed baled mulch is preferable to a loose mulch for mechanical spreading. Wheat, barley, and oat straws work well in blowers that shred, cut, and evenly scatter mulch. Rice straw does not scatter easily, it does not work well in a blower. Straw that is excessively brittle or is in an advanced stage of decomposition smothers or retards plant growth and should not be used.

Baled straw is long or short depending on agricultural practice used in baling. For anchoring mechanically, stems should not be less than 6 inches. In crimping, 50 percent of the fibers should average 10 inches or longer for incorporation into the soil to a depth of 2 to 2-1/2 inches and still leave tufts or whisker dams. On an equal-weight basis, standing residues are more effective than residues lying flat for wind erosion control. As a general rule, to hold wind erosion to a tolerable level of 5 tons per acre, about twice as much flattened residue than standing residue is needed.

Undesirable seeds harvested with straw may conflict with establishment of desired plant species.

Hay

Type of material: Long-fiber cellulose

Sources: Grass and legume hay crops

Packaging: Loose or baled (round, rectangular)

Availability: Local farms, farm stores (grain & feed),
prior reclaimed land

Measurement: Tons, Pounds

Properties:

Form: Fiber

Size: Minimum length, 6 inches; average, 10 inches

Color: Brown to Gray Green

Durability: One growing season

pH: 5.5

C to N ratio: Legume 19:1; grass 19:1 or less

Nutrients: lb/per ton, dry matter - N: 48, P: 10, K: 28

Application:

Intended use: Tons needed per acre - Seed cover: 2, Erosion control: 3,
Plant mulch: 4

Methods:

Application: Manual, spreader, or blower

Anchoring: Crimper or asphalt tackifier

Vegetative response: Weed seeds are usually present.

Comments: Hay requirements are much the same as straw. Source of supply may be undependable and prices are influenced by weather and demand. Cuttings of forage crops raised on previously reclaimed sites can be used for mulching on new reclamation projects.

Hay is available in 40- to 90-pound rectangular bales or 1,200- to 1,500-pound round bales depending on the kind of hay being baled and its moisture content. Hay comprised primarily of grass is as effective as straw. Fescue hay or other good grass hays are better because they last longer due to more stem and less leaves per volume than legumes.

On spring seedlings, hay decomposes rapidly reducing its efficiency in retarding surface runoff. It is more effective for fall seedlings because decomposition is not as rapid.

Alfalfa hay contains 43 percent carbon, 2.34 pounds of nitrogen with a C to N ratio of 18:1. Where used as a mulch, applications have significantly reduced pH in the surface 2 inches of mine soil. Very definite increases have occurred in the total quantity of exchangeable bases in soils. Nitric and carbonic acids produced during decomposition reduce the concentration of exchangeable calcium. Legumes should aid nitrification because soil nitrates tend to be slightly higher under them than under cereal straws. Areas receiving legume residues considerably out yield those mulched with cereal straws.

Hay is not as slippery as straw because long fibers lock together and restrict movement. The recommended minimum application rate is 3,000 pounds per acre crimped into the surface, a minimum depth of 1-1/2 inches and a maximum of 3 inches. Excessive rates can be a fire hazard in dry weather.

Application of hay is usually accomplished with a blower. However, processed hay containing maximum fiber length is capable of being hydraulically applied.

Mature hay and late season cuttings often are contaminated with seeds that conflict with establishment of desired plant species. Seed of grass and legume components may be beneficial on sites where a pasture is the post-mining land use. Native grass hay can add desirable native species on potential wildlife areas.

Manure

Type of material: Solid (long fiber), slurry, or liquid

Sources: Livestock and poultry excreta

Packaging: Bulk

Availability: Local farms, and beef, dairy, horse, swine,
or poultry operations

Measurement: Ton, dry matter basis; gallon

Properties:

Form: Fiber, solid, slurry, liquid

Size: Solid 2 to 6 inches

Color: Light to dark brown depending on fiber content

Durability: 6 to 12 months

pH: 6.6

C to N ratio: 25:1 or less (cattle)

Nutrients: lb/ton, dry weight

	<u>N</u>	<u>P</u>	<u>K</u>
Cattle manure	10.0	2.7	7.5
Poultry manure	29.9	14.3	7.0
Horse manure	14.9	4.5	13.2

Application:

Intended use: Tons needed per acre - Seed cover: 15, Erosion control:
30, Plant mulch: 40

Methods:

Application: Manure spreader, blower, tank truck, or
irrigation system

Anchoring: Slurries and liquids can be lightly disced
into surface.

Vegetative response: Manure is valuable as a source of plant nutrients. Lowered germination and reduced seedling growth can occur soon after application of animal waste.

Comments: Production of manure in some areas is great, and disposal is a considerable problem. Land application has been the traditional method for recycling animal wastes. However, because manure generates odor from collection through application, this practice is not socially accepted in heavily inhabited areas.

Animal wastes have higher solid to liquid concentrations (3:1) than those of municipal and industrial sewage wastes. Barn manure with a large amount of bedding material is mainly solid or semisolid. Because of the fiber in solid manure, it is less likely to adversely affect physical properties of the soil.

Manure should be covered during storage or confined in a lagoon, which would facilitate handling of both solid and liquid waste. A stockpiled material that is dry and friable is easier to load and spread than large chunks or fresh semisolid material.

Generally, soil pH will not be greatly affected by manure. Cattle wastes can increase soil pH, whereas poultry wastes can decrease soil pH.

Animal wastes contain large quantities of nitrogen and phosphorus. Manure ready for field application usually contains 0.5 percent nitrogen, 0.25 percent phosphoric acid, and 0.5 percent potash. Thus a ton supplies 10-5-10 pounds of these nutrients. Poultry and swine wastes are higher in nitrogen than most other manures. Chicken manures must be applied with more caution than others because of a high potassium and a high nitrogen content. Some manures have value as a mulch as well as a source of nutrients.

Animal wastes generate increased number of earthworms and other beneficial organisms. High content of organic matter in solids and slurries speeds the formation of soil.

Manure is recommended for 5:1 (20 percent) slopes or less. However, it can be used on steep slopes so long as outside water is not allowed to drain over the top and down the slope. Also, it is difficult to distribute evenly on steep slopes. On 10 to 12 percent slopes, soil loss on manure mulched-areas was 0.5 ton per acre compared to 12.5 ton per acre on unmulched areas. Applications of slurry and liquid manures aggregate sandy soils, reducing blowing by wind.

A minimum of 10 tons per acre is the recommended application rate that provides good cover against raindrop impact. Six tons of manure is approximately equal to 2 tons of crop residue.

Solid materials are applied by spreader or blower and should not be deposited in piles or windrows. Slurry and liquids are applied by irrigation systems or tank wagons. Wastes should not be spread on frozen soil or on actively melting snow because substantial nutrient losses can occur with surface runoff. Local precipitation records should be evaluated to avoid spreading wastes when runoff or leaching potential is high. Excessive manure application rates may lead to nitrate pollution of both runoff and ground water or may increase soil salinity through accumulation of sodium and potassium salts.

Annual crops are best adapted to manure applications because of the annual working of soil surface. Slight discing of manure into the surface greatly reduces odor.

Solids that are high in bedding material may depress plant growth unless supplemented with nitrogen fertilizer. High rates of manure application may cause high ammonia levels that may inhibit germination and plant growth. Accumulation of nitrate nitrogen can be toxic. Nitrates should leach from the soil but could accumulate in ground water. Grasses respond favorably to poultry wastes with seedling emergence triple that of untreated areas.

Another component of animal manures is weed seeds, necessitating careful vegetation selection and management practices. Manure storage may or may not decrease weed-seed viability.

Hardwood Bark

Type of material: Long fiber (shredded)

Sources: Deciduous woody vegetation

Packaging: Bulk--raw as it comes from debarker or processed from shredder

Availability: Residue from primary forest products industries or timber harvest on or off mine site.

Measurement: Ton, pounds, cubic yard (volume is preferred measure)

Properties:

Form: Fiber (shredded), ground, chunk

Size: 1/8 inch to 3 inches

Color: Light (straw color), reddish to gray brown

Durability: 3 to 4 years

pH: Fresh 4.2 to 6.4, composted 6.5 to 8.5

C to N ratio: 115:1 to 435:1, Average = 223:1

Nutrients: Percent - N: 0.1 to 0.2, P: 0.02 to 0.06, K: 0.05 to 0.32

Application:

Intended use:

	<u>Seed cover</u>	<u>Erosion control</u>	<u>Plant mulch</u>
Depth (inches)	3/8	2	4
Cubic yard per acre	45	240	480

Methods:

Application: Manual, spreader, blower, blower/impactor

Anchoring: Not required

Vegetative response: Hardwood bark produces a temporary nitrogen deficiency with no long-term effects. Inoculated legumes suffer no reduction in growth. Hardwood bark traps airborne seed.

Comments: Hardwood bark is readily available throughout the year in large quantities in localized areas in western, eastern, and northern Appalachian coal regions. It may be used raw as it comes from the debarker, or processed (hogged) to reduce to a more uniform size.

Bark is marketed on either a volume or weight basis. However, the relationship is important because weight is influenced by its moisture content.

Bark conserves moisture and is successful on the harshest of sites and during extended droughts when other mulches fail. It is superior to straw or hydromulch. Bark with high percentages of fines may act as a wick on droughty sites. However, when the particle size is larger than one-eighth of an inch, water retention is markedly reduced. Oak bark has a porous structure and requires one-third more depth than softwood bark to achieve similar moisture conservation results.

Bark has good insulating properties. Composted bark 1-1/2 inches deep may reduce temperatures by 40 to 50°F at 2-1/2 inches below the soil surface. Bark is 97 percent organic matter, containing 42 percent lignin and 55 percent carbon. It has a great variety of organic and inorganic compounds and elements. It may contain chelating agents that retain mineral plant nutrients. Organic acids may protect plant-available phosphorus against precipitation by calcium. Nutritional aspects of calcium, magnesium, and potassium may increase but with little difference in nitrogen or phosphorus. Bark has a high-cation exchange capacity, and the pH of leachate has a tendency to increase.

Bark contains little nitrogen and causes a nitrogen deficiency during decomposition. However, it is not as serious as problems with other wood mulches because the large individual particles decompose slowly due to the absence of cellulose. About 2 pounds of nitrogen per cubic yard can be added to bring the nitrogen concentration of the mass to 1 percent. Nitrogen requirements are usually higher for hardwoods than softwoods. An increase in plant-available phosphorus can result from the addition of shredded hardwood bark.

Bark is 11 to 15 percent of a tree's volume. Twelve hundred pounds of green bark by-product is generated with each thousand board feet of lumber produced. Conversion factor of weight to volume is 2.7 to 3.0 cubic yards per ton of mixed hardwood bark based on 50 percent moisture content, green weight basis. Moisture can vary with the time of year that logs are debarked and with the method used. For estimating, bark averages over 18 pounds per cubic foot or approximately 500 pounds per cubic yard.

Bark of shredded hardwood species has high density and is usually long, rough, and fibrous. Mulch should be graded to pass a 2-inch screen. The ratio of small, medium, and large particles determines the percentage of pore space and the effectiveness of the mulch to alter soil-moisture characteristics. Large particles assure high-porosity while fines raise the cation-exchange and moisture-holding capacities. Particle size should range between 3/16 inch to 1-1/8 inches for optimum soil stabilization.

Differences in properties of bark from various tree species are considerable. Barks from maple, poplar, and alder are typically high in cellulose (readily degradable carbon) and have a relatively high decomposition rate--40 to 50 percent in 60 days--and a nitrogen requirement of 1.0 percent by weight. Bark from all of these trees require 5 to 10 pounds of nitrogen per ton of bark to counteract C to N ratio during decomposition. Wood residues decay at a slower rate if used as a surface mulch; therefore, they demand less nitrogen for decomposition. When nitrate nitrogen depression is used as a measure of decomposition, hardwood residues may decompose 3 to 10 times more rapidly than residues from softwood. Rate of decomposition tends to increase with decreasing particle size. Very finely ground wood fiber or bark material will decompose at a very rapid rate because it increases the surface area for microbial attack. The absorption of water, nutrients, gas, and the attraction of particles for each other are all surface phenomena that influence decomposition. Thus, decomposition rates for these finely ground materials will be substantially higher and faster than that for coarse materials. Therefore, effective life of wood residues can in part be governed by selection based on particle size.

The older the tree, the smaller the ratio of cellulose to lignin. The lower the content of cellulose, the smaller the amount of nitrogen required when bark is used for mulch. Hickory, oak, and black walnut are resistant to microbial attack because there is less cellulose in the bark.

Composting removes some toxins and improves the bark as a mulch by forming humic acid. Optimum temperature for composting hardwood bark is 140 to 150°F. Optimum moisture is 50 to 60 percent on a wet-weight basis. Four weeks usually are required for composting plus 1 month stabilization.

Composting is not to be confused with stockpiling. Composting requires turning and other practices that induce a dark brown color.

When bark is stored in large stockpiles, decomposition takes place. If the piles are over 8 feet tall and 8 feet wide, anaerobic respiration takes place and organic acids that can be harmful to plants are formed. Bark should be kept in small piles so aerobic respiration continues and no harmful materials are produced. If acids are formed, the bark can be leached to wash out these organic acids or buffered with 10 pounds of lime per cubic yard. With proper methods, bark can be stored outside a year or more with little adverse effect. Bark is preferable if it has been weathered.

Hardwood bark mulch is a probable source of beneficial soil microorganisms, such as endomycorrhizal fungi. Damping-off fungi found on some bark mulch may affect success of direct seeding of conifers. Great numbers of mites may be found in bark compost, and these mites can initiate great populations of fungus gnats (Sciaridae sp.). Under field conditions, these organisms invade the partly fermented material in immense numbers and in a rather mysterious way. This invasion is one illustration of the symbiotic association of fungi and insects. A fungus (Fudigo septica) may develop large amounts of custard-like tissue on the bark surface, but it is not harmful and does not last for more than 1 to 2 weeks.

Ground bark is 1/50 to 1/8 inch in size. Excessive amounts of small particles can lead to compaction and anaerobic conditions. Loose bark aerates better. Under normal conditions coarse bark will not crust, blow, or wash away and particles 1 to 1-1/4 inches exert a favorable effect on the physical and chemical qualities of the minesoil.

Compared to wood chips, bark mulch is less subject to movement by wind and water because of the weight of the material and the long strands of rough-surface fiber that interlock. Long splintering particles stick well to the soil. They create a terrace effect as they lodge crosswise contributing to the effectiveness for erosion control.

The recommended optimum rate for good herbaceous cover is 30 to 50 cubic yards per acre, green weight. Thirty cubic yards (loose measure) of bark mulch per acre is recommended for application on north- and east-facing slopes that are 2:1 or less. Fifty cubic yards (loose measure) per acre is needed on slopes greater than 2:1, on slopes that face south and west, and for overwinter protection of disturbed sites. This provides a depth of 3/8 to 1/2 inch. Rates of 50 to 100 cubic yards per acre have little adverse effect on the emergence of most grass and legume species.

Where bark and straw have been tested side by side, leguminous vegetation with bark was more prompt and heavier and the distribution of plants was more uniform. High moisture content of bark material enhances rapid germination and growth of legumes in the early stages of development. Also, germination and growth may be hastened by the organic compounds in the bark leachate.

The effect of toxic components of bark on the establishment and growth of plants appears to have been overemphasized. Bark contains no weed seeds that would compete with desired species but will catch windborne natural seeds. The beneficial effects of using bark as mulch and soil conditioners for ornamental plants have been demonstrated by the continued and successful use of these materials by horticulturists and nurserymen. Considerably less is known about the use of these materials on woody vegetation on minesoils.

Surfaces that have been mulched with bark for surface protection before seeding do not have to be reworked for seeding to establish permanent cover. Broadcast seedings can be made on the surface of the mulch because seeds are "planted" in the voids between the mulch particles. A 2-inch layer of bark has supported a growth of grass that was sown directly on top.

Softwood Bark

Type of material: Solid to granular, shredded fiber

Sources: Coniferous woody vegetation

Packaging: Bulk--raw as it comes from debarker or processed

Availability: Residue from primary forest products industries or timber harvest on or off mine site.

Measurement: Ton, pounds; cubic yard (volume is preferred measure)

Properties:

Form: Ground, minichips, nuggets, chunk, shredded

Size: 0.25 inch, 0.25 to 0.75, 0.75 to 1.5 inches, 1.5 to 3.25 inches

Color: Reddish to dark brown to grays with aging

Durability: 5 to 10 years

pH: Fresh 3.5 to 5.5; composted 6.5 to 8.5

C to N ratio: Highly variable, 131:1 to 930:1

Nutrients: Percent - N: 0.76, P: 0.04, K: 0.25

Application:

Intended use:

	<u>Seed cover</u>	<u>Erosion control</u>	<u>Plant mulch</u>
Depth (inches)	3/8	2	4
Cubic yard per acre	45	240	480

Methods:

Application: Manual, spreader, blower, blower/impactor

Anchoring: Not required

Vegetative response: Softwood bark produces nitrogen deficiency with no long-term effects.

Comments: Softwood bark is readily available throughout the year in large quantities in the southern part of the Appalachian coal region.

Bark is measured in bulk form by the cubic yard. It is 8 to 24 percent of a tree's volume. Nine hundred forty pounds of green bark by-product is generated with each thousand board feet of lumber produced. Bulk density is 14 pounds per cubic foot, dry basis noncompacted or 17 pounds compacted.

Softwood bark contains approximately 98 percent organic matter with 55 percent lignin, 30 percent cellulose, 13 percent carbon sugars, and 2 percent inorganic matter. Eastern red cedar and various spruces are high in cellulose. Softwood bark needs 1 pound of additional nitrogen per cubic yard for decomposition to avoid nitrogen deficiency in plants. Since softwood decomposes more slowly, it requires about half the nitrogen of other wood residues for denitrification. Fresh pine bark requires 6 weeks of composting. Water-insoluble resins in softwood are largely responsible for slow decomposition. Cypress and white, shortleaf, longleaf, slash, and loblolly pines contain little cellulose. Therefore, little additional nitrogen is required. Because of a high content of acid compounds such as polyphenols, bark readily absorbs 2 percent nitrogen as ammonia. This is more than required for complete microbial decomposition. Cork bark rhytidome of older pine is resistant to decomposition due to suberin content. Thin bark of young pine has negligible amounts of rhytidome and has a pH about 5.4. Polymeric phenolic acids in softwood bark render it susceptible to many chemical reactions that might inhibit the growth of certain microorganisms.

Softwood barks (except cypress and cedars) are usually granular rather than fibrous and are not as porous as hardwood bark. Mulch should not contain a large proportion of fine particles, which may cause disagreeable dust and compaction of the mulch layer. Too many fines may result in poor drainage and root sloughing. A certain amount of fines is necessary because of the moisture-holding capacity. An optimum mulch contains the following size-class distribution.

<u>Percent of weight</u>	<u>Size class</u> <u>(inches)</u>
20	1 and over
10	1/2 to 1
20	1/4 to 1/2
20	1/8 to 1/4
10	1/16 to 1/8
10	1/50 to 1/16
10	greater than 1/50

Ground bark 1/8 to 1/4 inch is used primarily as a soil conditioner. Particles less than three-sixteenths of an inch do not give optimum performance for soil stabilization. Minichips, 1/4 to 3/4 inch, provide a good seed cover. Nugget size, 3/4 to 1-1/2 inches, is optimum for erosion control. Chunk size, 1-1/2 to 3-1/4 inches is right for mulching shrubs and trees. A 4 inch depth is most effective in smothering weeds.

Conversion factors for softwood bark: pine bark nuggets, 15 pounds per cubic foot, or 404 pounds per cubic yard, or approximately 5 cubic yards per ton. Pine bark minichips, 17 pounds per cubic foot, or 459 pounds per cubic yard, or 4.4 cubic yards per ton. Pine bark ground, 22 pounds per cubic foot, or 594 pounds per cubic yard, or 3.4 cubic yards per ton.

Softwood is less desirable than hardwood for erosion control because particles are granular, lighter in weight, and have a tendency to flow or move more easily in runoff water during heavy rains. Surface should be rough where softwood bark is used so that mulch particles can lodge in soil. The fibrous softwood barks (cedar and cypress) are recommended for erosion control when slope is a factor.

When the lignin fraction of pine bark begins to decompose, it releases a chemical similar to gibberellic acid, which has unusual plant growth stimulation.

Hardwood Chips

Type of material: Solid to granular
and platy

Sources: Deciduous vegetation

Packaging: Bulk--raw as it comes
from chipper

Availability: Pulp chips: product from
sawmills, veneer and chipping plants.

Whole-tree chips: mobile chip
harvesting on or off mine site.

Measurement: Ton, pounds; cubic yard

Properties:

Form: Solid chips

Size: 1/4 inch to 4 inches;
average length, 3/4 to 7/8 inch

Color: White to yellow, weathers tan to gray

Durability: 5 to 15 years depending on species

pH: Oak 4.1 to 6.0, average 5.3

C to N ratio: 615:1

Nutrients: Pounds per ton, dry matter - N: 4.0, P: 0.87, K: 3.32

Application:

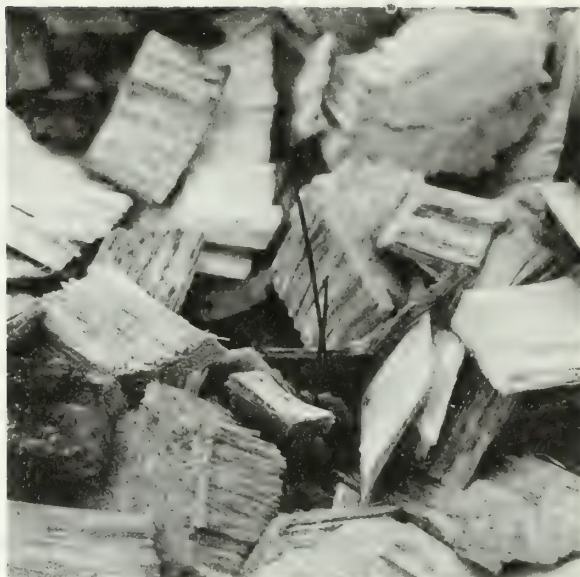
Intended use:

	<u>Seed cover</u>	<u>Erosion control</u>	<u>Plant mulch</u>
Depth (inches)	1/4	2	4
Cubic yard per acre	50	268	536

Methods:

Application: Manual, spreader, blower, blower/compactor

Anchoring: Not required



Vegetative Response: Hardwood chips produce temporary nitrogen deficiency with no long-term effects; inoculated legumes suffer no reduction in growth. Hardwood chips trap airborne seeds.

Comments: Hardwood chips are readily available from mills or whole-tree chipping operations throughout the year in western, eastern, and northern Appalachian coal regions. Supply seems to be more than adequate to satisfy mulching needs. There are 50 to 150 tons per acre of woody vegetation on typical Appalachian hardwood sites depending on age, quality, and past management practices. There are 70 to 120 tons per acre in eastern Kentucky even after sawlogs are removed.

Salvage and conversion of woody vegetation that is usually wasted on a mine site during clearing operations can be a source of wood chips. If the mine area has 100-ton-per-acre vegetation, only 1/4 to 1/3 of the wood chips potential would be needed for mulch. Initial cost may be more than other mulches, but performance is better and cost may be less in the long run if no maintenance is required. Costs can be reduced by on-site chipping, which would be part of clearing and grubbing costs rather than reclamation costs. They are produced from the entire aboveground portion of trunk, limbs, and branches and are usually used without further processing. They are marketed on either a volume or weight basis. However, rates of application are expressed in cubic yards because chips show extreme variation in moisture content. Rates relating to weight must be based on air-dry weights to assure uniformity. Conversion factors from weight to volume are influenced by the species composition of the chips. A ton of green oak chips contains about 4 cubic yards while a ton of red maple has nearly 5 cubic yards. A weighted average used by paper companies in estimating green chips is 18 pounds per cubic foot or 500 pounds per cubic yard or 4.0 cubic yards per ton. Fine chips average about 17 pounds per cubic foot and coarse, 24 pounds per cubic foot.

Chippers can be adjusted to produce chips 1/4 inch to 4 inches in length. Chips should not be larger than three-eighths of an inch thick or more than 6 square inches (2" x 3") in area and should be graded through various size sieves to blend particle sizes. Small particles retain more moisture but can interfere with drainage. Large chips absorb less moisture and provide good drainage.

Chips are 98 percent organic matter, with an average of 26 percent lignin and 72 percent carbon. Forty-five percent of green weight is water. Fourteen to eighteen percent of dry weight of whole-tree chips is bark. In summer, an additional 1 to 2 percent is leaves.

Denitrification is not a serious problem with wood chips because the particles are larger and usually decompose more slowly than crop residues or wood fibers. Chips decompose faster than bark because of a higher cellulose content. They settle naturally, needing no compaction and remain in place for 8 to 15 years, depending on species of wood and depth of coverage.

Nitrogen is utilized during chip decomposition. Fifty pounds of nitrogen per ton of wood chips can be applied in stockpile so decomposition starts before application. Composting wood residues aerobically for 3 months or more also helps. Application of 45 to 50 cubic yards per acre under normal seeding and fertilization practices normally does not cause a nitrogen deficiency. One pound of nitrogen per 100 pounds of chips or 20 pounds per ton is a rule-of-thumb for adding nitrogen to chips to prevent soil denitrification.

The amount and causes of microbiological deterioration of wood mulches during storage are important. For example, if wood chips are to be stored for any length of time, a full assessment of the destructive capabilities of organisms, particularly those known to be prevalent in chip storage piles and capable of causing substantial weight losses in wood, is desirable. Fungi grow prolifically within a wood-chip pile creating heat. This warmer environment encourages growth of "heat-loving" fungi, which replace some of the earlier fungi that are restricted as the temperature rises above 104°F. Temperatures rise to 122 to 140°F and higher in chip piles. Temperatures above 150°F kill virtually all fungi in a pile. Ideally, storage should not exceed 2 to 3 months for hardwood chips and 4 to 5 months for softwood chips piled in above-freezing weather. Hardwood chips stored outside average a loss in weight of 5.5 to 7.5 percent. An average weight loss of 1 percent per month can be expected, and losses up to 2 percent per month have occurred in some hardwood chips.

Any soil acidity increase caused by wood product decomposition is negligible. Wood mulches are strongly acid and pH values range from 3.5 to 7.0 with an average of 4.5. The effects that decomposition of the products may have on soil reaction are of greater importance than the initial pH. The end product is alkaline-like wood ashes. Since the ash of these products contains more basic than acidic constituents, the pH should increase with the ultimate effect toward a less acidic condition.

Application rate of chips must be at least 6 times that of straw to obtain the same surface protection as straw. The recommendation is 10 to 20 tons per acre or 40 to 60 cubic yards. This provides a depth of 3/8 to 1/2 inch, which is adequate for protecting the soil surface and enhancing germination and establishment of most seedlings. A 2-inch layer of mulch is an effective erosion deterrent on steep denuded slopes up to 150 feet in length. A 1-inch cover of chips is not sufficient to provide erosion control on slopes steeper than 3:1. However, a 1-inch layer of chips controls erosion better than 2 to 3 tons of straw per acre. Four-inch layer of chips is effective on slopes between 4:1 and 1:1 when used purely for erosion control and will remain in place 8 to 15 years.

Partially decomposed wood products are preferred because they tend to be less susceptible to movement. The ragged edges of chips mesh and hold each other in place. However, when dry, chips are more subject to movement by wind and water than hardwood bark. Chips are more effective than standard wood-fiber mulch in preventing soil erosion.

Chips invariably will affect vegetative growth unless supplemental nitrogen is added or they are composted before application. Because of their size and weight, chips can inhibit seed emergence. Depths of 3 to 4 inches retard the establishment of grasses. Layers less than 2 inches are preferred when used for establishing herbaceous cover.

Chips do not contain weed seeds but do trap airborne seeds. They do not create a fire hazard and do not favor insects or rodents.

Softwood Chips

Type of material: Solid to granular and platy

Sources: Coniferous vegetation

Availability: Pulp chips: product from sawmills, veneer plants, and chipping plants. Whole-tree chips: mobile chip harvesting on or off mine site.

Measurement: Ton; cubic yard

Properties:

Form: Solid chips

Size: 1/4 inch to 4 inches; average length, 3/4 to 7/8 inch

Color: White to yellow, weathers tan to gray

Durability: 5 to 15 years depending on species

pH: 3.9 to 5.1

C to N ratio: 615:1

Nutrients: Percent - N: 0.138, P: 0.020, K: 0.102

Application:

Intended use:

	<u>Seed cover</u>	<u>Erosion control</u>	<u>Plant mulch</u>
Depth (inches)	1/4	2	4
Cubic yard per acre	50	268	536

Methods:

Application: Manual, spreader, blower, blower/compactor

Anchoring: Not required

Vegetative Response: Softwood chips produce temporary nitrogen deficiency with no long-term effects; trap airborne seeds.

Comments: Softwood chips are available throughout the year in the southern part of the Appalachian coal region. Chips are usually used without further processing. They are produced from entire aboveground portion of the trunk, limbs, branches, and needles. Whole-tree chips are about 83 percent wood, 13 percent bark, and 4 percent needles.

Chips contain 98 percent total organic matter with an average of 28 percent lignin and 69 percent carbon. Softwoods usually contain more lignin than hardwood. Carbohydrate fraction is 70 percent of the weight of wood.

Chips are marketed on either a volume or weight basis. Rates relating to weight must be based on air-dry weight to assure uniformity. White pine chips average 13 pounds per cubic foot or 5.7 cubic yards per ton. In general, pine is more effective than oak hardwood in improving the soil. Pine decomposition is much slower and usually more acid than hardwood. High lignin content, greater concentration of resinous compounds, and the less porous structure in softwood are probably the major factors contributing to slower initial decomposition of softwood. Cedar contains toxic materials that, under certain conditions, adversely affect the growth of some plants.

Softwoods require about 15 pounds of nitrogen per ton for decomposition. Maximum nitrogen immobilization is reached in 80 to 160 days.

Sawdust

Type of material: Solid to granular

Sources: Deciduous and coniferous vegetation

Packaging: Bulk

Availability: Local sawmill, forest products industry

Measurement: Ton; cubic yard

Properties:

Form: Granular to green air dried, kiln dried, composted

Size: 8 to 40 mesh

Color: Light yellow darkening with weathering

Durability: 3 to 5 years

pH: 3.5 to 7.0, average 5.2

C to N: 200:1 to 500:1

Nutrients: Pounds per ton, dry matter - N: 4, P: 2, K: 4

Application:

Intended use:

	<u>Seed cover</u>	<u>Erosion control</u>	<u>Plant mulch</u>
Depth (inches)	1/2	2	4
Cubic yards per acre	65	260	520

Methods:

Application: Manual, spreader, lime/fertilizer

Anchoring: Chemical, asphalt tackifier

Comments: Sawdust is readily available throughout the year in large quantities in western, eastern, and Appalachian coal regions. It may be used raw, weathered, or composted. It is available as green, air dried, kiln dried, or composted. Well weathered sawdust, leached for at least 1 year, is the most desirable. Some objectionable features in handling sawdust are slivers and dust.

Sawdust is often graded for size and in some instances by species. Hardwood sawdust is sifted in 8 to 40 mesh, while softwood is not.

In the production of a thousand board feet of lumber, pine produces 1 ton of sawdust; soft hardwood, 0.95 ton; and hardwood, 1.10 ton. There are 775 to 800 pounds per cubic yard or about 2.5 cubic yards per ton.

Sawdust is capable of absorbing water at 2 to 6 times its own weight. It can have a wick effect under certain conditions. Because of its small particle size, sawdust tends to pack tightly, and thus retard aeration and infiltration.

Decomposition of sawdust is more rapid than that of other wood residues because of the more finely divided materials and high cellulose content. However, decomposition rate is slower than that for an equal weight of straw.

Sawdust includes tannins and phenolic compounds injurious to plants and soil microbes, and its high cellulose content results in a high C to N ratio. This leads to the impoverishment of soil in nitrates and ammonia consumed by carbohydrate-decomposing organisms. Toxicity may be avoided by the application of 25 pounds of nitrogen per ton of dry sawdust. This corresponds to 115 pounds of ammonium sulphate or 72 pounds of ammonium nitrate.

The lignin in sawdust is valuable in the maintenance of soil fertility. The carboxyl groups of this high-molecular aromatic compound have an ability to part with hydrogen and retain adsorbed ions of ammonia, calcium, magnesium, potassium, and other bases. In this manner, lignin acts as a storehouse of nutrients that are preserved from leaching and yet are available to plants through the exchange reactions.

Most sawdusts are slightly acid: changes in the pH of the mixture depend on the wood species. If sawdust is strongly fermented, pH may decrease. Yellow pine, spruce, white, and black oak sawdusts have a pH of 4.1 to 5.0; red pine, maple, red, and pin oak 5.1 to 6.0. Sawdust has little effect on soil acidity, but if it is applied to areas requiring lime, any acid in it may be slightly harmful. Any acidity in sawdust can normally be neutralized with the application of 100 pounds or so of finely ground limestone per ton of dry material.

Sawdust can be used at high rates, but its nitrogen requirement may be the factor determining practical limits to the rate of applications. Small, granular particle sizes that are light in weight make sawdust subject to floating or blowing away. Sawdust performs less favorably than most other mulches on slopes. Sawdust applied at the rate of 30 cubic yards per acre on a 3:1 slope was severely eroded after a simulated 6-inch-per-hour rainfall that lasted 30 minutes.

Sometimes sawdust has a depressive effect on plants but that can be overcome by the addition of nitrogen. No weed seeds are found in the mixtures.

Leaves

Type of material: Short fiber

Sources: Deciduous trees

Packaging: Whole leaves--bulk or
compacted bales, composted--bulk

Availability: Local municipalities

Measurement: Ton, whole leaves or
shredded; cubic yard, composted

Properties:

Form: Whole leaves, shredded, compost

Size: Variable

Color: Yellow to dark brown

Durability: One growing season

pH: Composted, 6.5

C to N ratio: 40:1

Nutrients: Percent N: 1.28

Application:

Intended use: Tons needed per acre - Seed cover: 3, Erosion control: 4,
Plant Mulch: 5

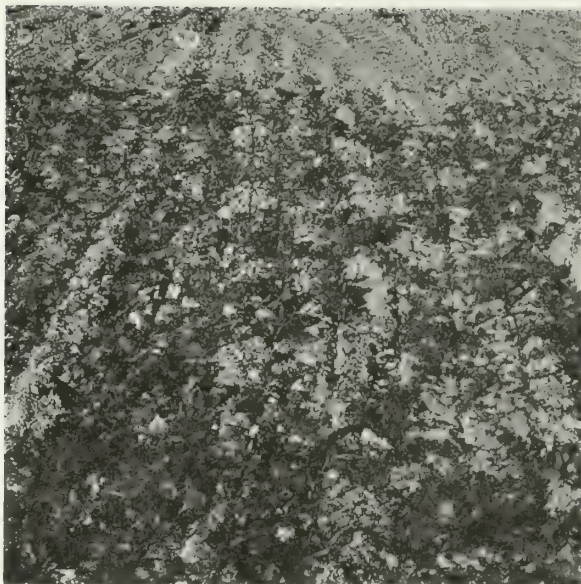
Methods:

Application: Manual, spreader, blower

Anchoring: Whole or shredded leaves crimped lightly

Comments: Leaves are available in the fall from communities in the western and eastern Interior and the northern Appalachian coal regions. Ordinances banning or prohibiting open burning have created a surplus of leaves. They may be used whole (unrotted), shredded, or composted.

Availability of whole leaves does not coincide with the time when they are needed. Usually, fall seeding is accomplished before leaves are available. If they are baled and covered, they can be held until spring.



Little data exists on the use of leaves as a surface mulch on large disturbed areas. Leaves are an important source of organic matter (leaf mold). They contain 53 percent carbon and 26 percent cellulose, dry weight. Application rates are similar to straw and hay. Excessive rates could be a fire hazard. Bales of whole leaves may contain foreign debris such as twigs, rocks, sand, and plastic bags that should be removed before mechanical application.

Leaves are usually composted and screened. Composting requires about 200 days. Every 4 cubic yards of whole leaves yield approximately 1 cubic yard of compost. Use of leaves is limited to level areas and slopes less than 3:1 because light discing to a 2-inch depth is necessary to hold leaves in place. A 2- to 3-inch layer of partly rotted leaves will break down fast enough to add plant food and humus to soil.

Solid Waste

Type of material: Short fiber

Sources: Processed or composted garbage

Packaging: Bulk--shredded or composted

Availability: Municipalities or commercial waste-recovery plants

Measurement: Ton; cubic yard

Properties:

Form: Fiber

Size: 1 to 2 inches shredded, 1/2 inch after composting

Color: Grayish green to grayish black

pH: Compost 7.5 to 8.5

C to N ratio: Unprocessed, 45:1 to 55:1

Nutrients: Percent

	<u>N</u>	<u>P</u>	<u>K</u>
Compost	1.0	.25	.25

Application:

Intended use: Tons needed per acre - Seed cover: 20

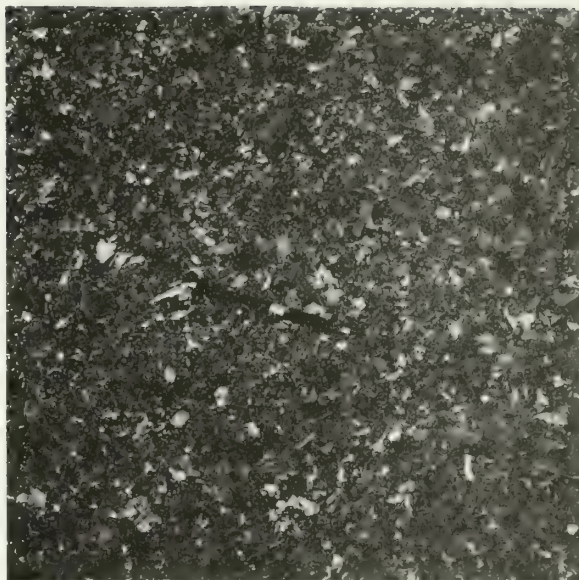
Methods:

Application: Manual, spreader, blower/impactor

Anchoring: Light discing

Vegetative response: Solid waste has beneficial effects on plant growth

Comments: Solid waste is available shredded or as a compost from communities and as commercial products. Shredded municipal refuse contains a considerable amount of solid fragments (glass, plastic, metal) that are not readily biodegradable and may detract esthetically when applied to land. Waste material that has been sorted to remove these fragments and other inorganic material is most desirable.



There has been increased use of the organic/compost fractions of refuse. Composting is an ancient practice. It is a microbiological process that depends on the growth and action of mixed populations of bacteria and fungi that are indigenous to various organic wastes. One of the major advantages of composting solid wastes is that it helps to abate problems of objectionable odor, human pathogens, and undesirable physical properties associated with utilization of organic wastes.

Composting results in a 40 to 50 percent reduction in volume and weight. C to N ratio of refuse can be lowered by the addition of sewage sludge during composting. Garbage should be shredded to 1 or 2 inch lengths and woody material to 1/2 inch for composting.

Solid waste compost is most valuable as a soil conditioner. It promotes soil aggregation which enhances the air-water relationship of soil. Compost usually possesses a full complement of trace elements.

Composted municipal waste reduces acidity. It provides increased buffering capacity due to the rapid change in soil acidity and alkalinity and neutralization of certain toxic substances. Constraints on solid waste can be excessive C to N ratio or high concentrations of elements and metals if excessively applied. Up to 20 dry tons per acre can be applied without overfertilizing. Twenty-five to seventy-five tons per acre would provide a more stabilized organic layer. Generally, applications up to 40 to 50 tons per acre are not excessive if added in spring. Dried and ground substances can be applied with blower/impactor and then lightly disced. Solid waste is eroded by heavy rainfall. Light-weight and small particle-size characteristics of solid waste do not hinder surface runoff. So, the solid waste becomes saturated and incorporated with soil particles. It cannot be held effectively on a slope. However, fibers do hold the soil better than no mulch. There are no weed seeds in solid waste.

Wastewater Sludge

Type of material: Solid, liquid

Sources: Municipal and industrial sewage sludge, residential septic sewage

Packaging: Bulk--dewatered sludge, slurry, liquid

Availability: Municipal and industrial treatment plants and septic tank cleaning companies

Measurement: Ton; gallon

Properties:

Form: Solid, slurry, liquid

Color: Dark, gray to black

Durability: 90 days

pH: Solid, 5.7 to 6.8

C to N ratio: 25:1

Nutrients: Percent dry weight basis

	<u>N</u>	<u>P</u>	<u>K</u>
Dry Sludge	3.5 to 6.4	0.8 to 3.9	0.2 to 0.7
Slurry	2.9 to 8.0	3.0 to 7.0	0.3 to 0.6
Liquid	1.7	1.4	0.4
Compost	0.6		

Application:

Intended use: Dry ton per acre for disturbed lands - Seed cover: 23-375

Methods:

Application: Solid--spreader, Slurry--water tight box spreader,
liquid--hydraulic sprinkler, tank truck

Anchoring: Light discing

Vegetative response: Wastewater sludge provides significant beneficial effects on plant growth.

Comments: Sludge is a good, inexpensive, and readily available source of organic matter. Pipeline, railroad, truck, or barge is used to transport various forms of sludge from distant communities. Dewatering sludge permits hauling less water to projects and permits prolonged storage. Land application of sludge is not acceptable without further stabilization such as digestion, composting, or lagooning.

Projects receiving sludge should be provided with an analysis before application showing pH, percent of solids, nutrients, and heavy metals. Sludge should be stabilized to yield a product that is equivalent to that obtained by anaerobic digestion for 10 days at 78 to 110°F. Digested or stabilized sludge has minimal odor. Sludge direct from the digester averages 5 percent solids.

Sludge is about 50 percent organic matter, dry weight. Sewage effluent and liquid digested sludge are very low (about 3 percent) in BOD (biological oxygen demand) material. It provides no significant increase in organic material except for organic inputs from increased vegetative growth due to nutrients from sludge.

Many problems associated with the use of sludge can be overcome by composting. A composted stabilized sludge will add organic matter through the introduction of a bulking agent such as wood chips or bark. Wood chips mixed 3:1 with sewage sludge on a volume basis (1:1 weight basis) induce crumbling of sludge producing a rich form of compost. The wood residue provides a structure throughout the mass for air movement and absorption creating a blotter-like effect that lowers moisture content of the biomass to an optimal content of 50 to 60 percent by weight.

One of the advantages of composting is the conversion of sludge into a product that can be handled with a minimum of difficulty and in a manner that is both environmentally and hygienically sound. In the digestion process, a temperature of 95°F or above lowers human and plant pathogen content. Optimal temperatures for composting range from 140 to 160°F. Rapid composting occurs when the C to N ratio is 25:1 to 35:1 and a continuous supply of oxygen is available. It takes about 3 weeks to compost sludge by aeration. Compost is dried, screened, and cured. When chips are used as the bulking agent, about half of them become part of the compost and the balance is reused.

Digested sewage sludge does not hinder microbial activities or restrict their populations. Reduced acidity in the surface spoil layers from alkaline effluent and sludge creates a more favorable environment for autotrophs such as nitrosomonas and nitrobacteria. Increased microfungal derivatives are most likely due to the accompanying elevation in pH, resultant higher levels of organic matter, and improved water-holding capacity. The effects of these factors on microfungal activity can show up to a fourfold increase in the density of the fungal population compared to that on untreated mine soil.

In general, effluent and sludge improve the chemical characteristics of mine soils and provide a source of nutrients needed for successful vegetation. Sludge colloids absorb soluble nutrients preserving them from loss through leaching and making them available to plants. Effluents have increased cation-exchange capacity and contain significant quantities of bases, calcium, magnesium, and sodium. Effluents are effective in diluting salt concentrations and can reduce the concentration of toxic elements by leaching them below plant-rooting depth.

Most digested sludges have a greater fertilizer potential than that of composted sludge. Nutrient content is reduced by composting and the dewatering and drying process. Sludge contains only about 5 percent nitrogen, dry weight. Only about 10 percent of nitrogen in compost is available at application, and the remaining 90 percent in organic form is unavailable until mineralization occurs, releasing nutrients slowly over a long period of time.

Phosphorus is present in both organic and inorganic forms. The soluble phosphate is directly used by plant roots and the excess is strongly held to the soil particles. Proportion of phosphorus to nitrogen in sludge is higher by a factor of 5 or more than the proportion needed by a plant.

Sludge and softwood-bark compost with a pH of 6.0 to 7.0 increase pH of minesoils. Alkaline effluent has a flushing action on acid spoil leachate. It effects the greatest pH changes in the plant rooting or surface 6 to 12 inches, resulting in immediate significant increases.

Metals and certain toxic substances in sludge may be phytotoxic to plants. Some organic chemicals endanger the food chain after absorption and accumulation. Elements that are most likely present in concentrations toxic to plants are aluminum and manganese. On acid minesoils, metal concentrations may increase unless enough material is applied to effectively neutralize the acid spoil or raise it above the critical level of 4.0. There is little uptake of heavy metals by plants when pH is greater than 6.5.

Characteristics of sludge vary widely due to the great difference in type and source of wastewater and in the design and operation of wastewater treatment plants. Plumbing in buildings is cause for high concentrations of copper, zinc, and lead; greater amounts of metals are expected in wastewater from heavy machinery, battery, and plating industries. Sludge application rates should not cause heavy metal additions to land.

Excess nitrogen leaching into groundwater, presence of pathogens, and some odor are primary nuisances involved with land application of sewage sludge. Nitrogen in sludge is usually the factor that limits the amount to be applied. Rates should not exceed plant needs. If nitrate-nitrogen is applied or formed at a greater rate than it can be removed by plant uptake, denitrification, and microbial use, the excess nitrates are likely to contaminate ground or surface water.

For reclamation, rates may need to exceed those used on croplands. Two 1-inch applications per week are most commonly used for reclamation and supply about 10 pounds of nitrogen per acre. Two inches of sludge provide about 13 tons per acre, dry matter. An application of 2 dry tons per acre is equivalent to approximately 19,500 gallons or 1/4 inch of liquid. This liquid contains 2 to 45 tons per acre of solids with a pH of about 7.

Solids in dry form are applied much like animal manure. Dewatered sludge, which is 20 to 30 percent solids, is applied with a rear discharge truck or manure spreader. Septic tank wastes are applied to the land with a tank-truck injection system or by tank-truck surface spreader. Application should be in isolated areas at least 500 feet from nearest residence.

Slurries can be hauled directly to the field with a tank wagon or diluted with water and pumped to the area through pipeline irrigation equipment. Slurry eliminates dewatering and eases application by irrigation, but creates more material to transport. Additional energy and transportation costs for slurry need to be weighed against that for dewatering.

Liquid forms are applied by tank trucks, gravity flow, pressurized systems, surface sprayers, subsurface soil injection or sprinkler (spray) irrigation, and flood furrow. Spray irrigation provides the highest uniformity and is the most frequently used type of liquid application. It involves construction of distribution lines, either stationary or movable, pumping equipment, and storage lagoon.

Spray irrigation of treated sewage effluent helps to moderate surface temperature of dry minesoil by direct heat transfer to the water and cooling of the surface as it evaporates. In spraying, one has to be careful not to coat the leaves of plants with so much sludge that it interferes with photosynthesis and respiration. Sludge content of 6 percent solids is the limit for spraying. Sludges with over 10 percent solids do not flow by gravity through a 6-inch pipe.

Sludge should not be spread on slopes greater than 12 percent. If sludge is applied on slopes greater than 5 percent, material runoff should be retained by use of contour strips, terraces, and border areas. Liquid wastes usually are not spread on land where the erosion and runoff potentials are great. Good management implies that liquid wastes on rolling or hilly land should not be applied in excess of the infiltration capacity or in a volume greater than the surface layer can absorb and retain.

Wood-Cellulose Fiber

Type of material: Short fiber

Sources: Natural virgin wood-cellulose fibers produced from wood chips or recycled wood pulp.

Packaging: Bags, 50 to 60 pounds; bales, 800 to 1000 pounds

Availability: Manufacturers of commercial products made from above sources

Measurement: Ton, pounds (Air-dry weight)

Properties:

Form: Shredded

Size: 0.5 inch

Color: Natural or green (temporary dye)

Durability: Effective for 30 days after application

pH: Conwed, 4.8, turf fiber, 7.0

Application:

Intended use: Pounds needed per acre - Seed cover: 1,500, Erosion control: 3,000

Methods:

Application: Hydroseeder mulcher

Anchoring: Chemicals used in special situations

Vegetative response: Wood-cellulose fiber contains no germination or growth-inhibiting factors. It is free from chemical additives and foreign matter that inhibit growth.

Comments: Wood-cellulose fiber mulches are usually either wood or paper fibers. Material is readily available and inexpensively produced from reprocessed wood-pulp chips or recycled paper products. It is available in bags or bales, which can be easily handled and conveniently stored for long periods.



Wood-fiber mulch is desirable where rapid mulching of an area is essential. It is considered comparable to straw or hay but does not last as long and is less effective in reducing surface temperature, conserving moisture, and in preventing erosion.

Effectiveness is roughly related to the size and shape of the fiber. Long, narrow fibers are superior to short, finely ground products. Wood fiber is longer and therefore more desirable than paper fiber. Virgin wood fibers of aspen, alder, or hemlock seem to last longer and are consistently superior to all other fibers. Recycled office wastes and newspaper are less effective but could be improved if fiber length was increased. Because it has long fibers, the waste corrugated box can be recycled into a product nearly equal to that of virgin wood.

Wood fibers are cut at a slight angle that allows splintering of fiber when weathering. Even with high application rates, short wood fibers break down very rapidly, and little mulch remains on the surface 8 weeks after application. This rapid decomposition reduces its efficiency in moisture conservation. However, no additional nitrogen is required for decomposition. Another mulch usually must be considered where surface protection is to be maintained more than 30 days.

Wood fiber and wood cellulose have equal value if applied at the same dry weight. They are free from chemical additives and foreign matter that inhibit growth.

The common application rate on slopes flatter than 4:1 is 1,500 pounds of mulch per acre and 1,500 to 2,000 pounds per acre on steeper slopes. This provides only minimal coverage with no consistent beneficial effect observed with less than 1,500 pounds and little or no benefit from 1,000 pounds. During periods of stress, 1,500 pounds of wood fiber is not as effective as 3,000 to 4,000 pounds of straw or hay. It takes 2,000 to 3,000 pounds per acre of wood fiber to produce a true mulch effect.

Wood-fiber mulch is mixed with water, seed, and fertilizer to form a slurry and is applied in a one-step operation with a hydroseeder mulcher. A 2,500-gallon hydroseeder with a 1,500-pound-per-acre rate can cover 0.6 acres per each load of material or about 4.8 acres per day.

The hydromulching process offers a high degree of control in placement. Material can be sprayed into inaccessible areas, notably steep slopes. It can be sprayed with good precision even in a strong wind.

Consistent uniform size and texture of mulch disperses uniformly and evenly on the surface. A nontoxic, water-soluble, green dye is used on the mulch to facilitate uniform distribution and to provide a pleasant finished look to the newly mulched area. Color fades in about 3 to 5 days.

When applied with seed, fiber-mulch applications are restricted to recommended planting dates for the seed mixture. There is evidence that fiber mulches may reduce the percentage of seeds germinating and slow plant growth. Hydromulch has a tendency to keep seed from making direct contact with mineral soil by leaving the seed suspended in the mulch where it is more susceptible to moisture stress during wetting and drying cycles. A high percentage of the seedlings have little or no chance of getting their primary roots into the soil. Higher seeding rates may be used to compensate for these losses, or the seed can be applied in one application and the mulch in a second application.

Slopes should be left rough before hydromulching to facilitate adherence of mulch to the soil surface. The fibrous mat of the mulch provides initial protection and resistance against erosion. However, it breaks down rapidly in heavy rain. Recycled paper-cellulose fiber does not hold seed in place as well as wood fiber and provides less erosion protection. On sandy soils, fiber mulch does not control wind erosion as efficiently as other materials.

In general, wood-fiber mulch does not develop better grass or legume starts than those on unmulched areas. Seedlings of legumes come in more slowly when applied in hydromulch. Cereal grain seeds are subject to germination damage if left in the tank in direct contact with concentrated fertilizer in suspension over 45 minutes before application. However, wood fiber is weed free, nonpolluting, clean, and biodegradable.

Adherence to proper mulching rates and application procedures will greatly enhance success in establishing vegetation and in protecting the minesoil from erosion. In this section, information is discussed on surface preparation, application rates, time of application, methods, anchoring techniques, and equipment.

Surface Preparation

The finished minesoil surface must be suitable for vegetation establishment. Practices for preparing the minesoil surface for seeding are applicable to mulching since it is part of or immediately follows the seeding operation.

The landform design and the effects of backfilling, grading, and topsoiling the mined surface for reclamation should be carefully considered. Some design and construction practices produce surface conditions that are not always necessary or appropriate for applying seed or mulch.

Grading practices on some minesoils, especially those with a predominance of clay and silt particles, can actually hinder successful runoff control and vegetation establishment. Disturbing and grading wet or muddy minesoils or tilling and leveling dry material to a fine smooth finish alters the physical properties of the minesoil, creating compaction and other undesirable surface conditions.

Often, there is a tendency to unnecessarily finish, grade, or manicure the prepared surface. The surface should be left as rough as possible without disrupting the approved postmining land use. Contoured furrows, ripped strips, or other rough tillage are preferable to the smoothly graded and harrowed surfaces. A properly roughened, cloddy, and loosened surface will enhance mulch adherence; reduce evaporation; provide numerous depressions that will intercept and slow surface runoff and retain moisture; create ridges that protect against abrasion by windblown soil; and provide pockets that trap and hold sediment, improve water infiltration, and benefit plant growth.

Roughening of the soil surface by mechanical means with a large-particle mulch can, on some soils, completely stay wind and water erosion temporarily. Every stone, clod, unevenness of the ground, particle of mulch, or other obstacle in the path of wind or running water retards their movement and consequently the cutting and transporting capacity of these agents. The optimum variations in the height of the roughened surface for effective wind erosion control are from 2 to 6 inches. Coarse mulch in combination with a rough surface will almost eliminate wind surface creep. Additionally, a 3-inch ridge will trap about 60 percent of the flow in saltation.

Slopes should be designed and constructed as flat as economically possible. As slopes become steeper, erosion-control cost increases rapidly and the effectiveness and performance of control measures decrease. Where possible, slopes should be designed with gradients reduced to a degree that will provide mechanical stability with adequate rounding at both top and bottom and with appropriate transitional grading in between. This will improve appearance, facilitate vegetation establishment, and reduce maintenance costs.

The purpose of grading and shaping the slopes is to reduce the erosive forces of water and retain it on site for use by vegetation. On steep slopes, it is desirable to keep soils loosened, mulched, and if possible, somewhat ridged at right angles to the slope. All final grading and tillage should be performed on the contour; back blading that results in a smooth compacted surface should be avoided.

Application Rates

The selection of the optimum rate and depth of a mulch is influenced by intended use and the effectiveness of the mulch in modifying environmental factors associated with the site conditions. Soil and seed protection, erosion control, and growth enhancement are the main purposes for use of mulch and are the most logical components on which to base application rates (Table 10).

An important consideration in the efficient use of mulch is that of mulch depth in relation to application rate (Table 11). Also, the particle size and correct amount of mulch is directly related to the proper depth at which to apply the mulch. For example, 135 cubic yards of bark minichips will cover 1 acre 1 inch deep whereas it takes 160 cubic yards of chunk bark for the same coverage. Coverage with straw at 1-1/2 tons per acre provides about a 1-inch layer. The rate and depth of application varies due to the type of material and particle size.

Coarse and more bulky materials may be applied in greater depths than those of small materials that will compact. The selected material should be sufficiently loose and open for free circulation of air to favor development of vegetation.

Seed Bed Cover

The quantity of mulch needed at a specific site varies with soil surface and seeding conditions; species of plants to be seeded; and their requirements for germination, seedling emergence, and establishment. Therefore, mulch should be applied at a rate that will provide the necessary protection for the soil surface yet not prevent seed germination and emergence.

Cover mulches are usually applied at depths from 1/4 inch up to a maximum of 2 inches depending on the type and size of material (Fig. 8). Depths greater than 2 inches will begin to significantly affect germination and emergence of seedlings. The optimum depth of mulch for seed cover is related to seed size. If the mulch is too thick or tightly matted, the seedlings may not have sufficient energy to penetrate the layer. The smaller the seed, the less energy available to emerge. For small seeded species, such as lovegrass or timothy, emergence is likely to be reduced where they are covered with more than 1/2 inch of solid mulches such as bark. In situations where higher rates of mulch are needed or required, increase the seeding rates of species with small seeds to compensate for the reduced emergence, or select vegetation species with larger seeds that would be compatible with the higher rates.

Table 10. Common application rates per acre

Mulch	Intended Use		
	Seed cover	Erosion control	Plant mulch
Straw (ton)	1.5-2	3	4
Hay (ton)	2	3	4
Manure (ton)	10-15	30-40	40-60
Hardwood bark (cubic yard)	45	240	480
Softwood bark (cubic yard)	45	240	480
Hardwood chips (cubic yard)	50	268	536
Softwood chips (cubic yard)	50	268	536
Sawdust (cubic yard)	275	550	825
Leaves (ton)	3	4	5
Solid waste (ton)	20	---	---
Sewage sludge (ton)	75	---	---
Wood-cellulose fiber (pound)	1,500	3,000	---

Table 11. Coverage of mulch by depth and intended use

Depth (inches)	Intended use	Coverage per cubic yard ^{a/} (square feet)
1/4-2	Seed bed cover	1,728-162
2-4	Erosion control	162-81
4-6	Plant mulch	81-54

^{a/} Coverage varies depending on particle size.

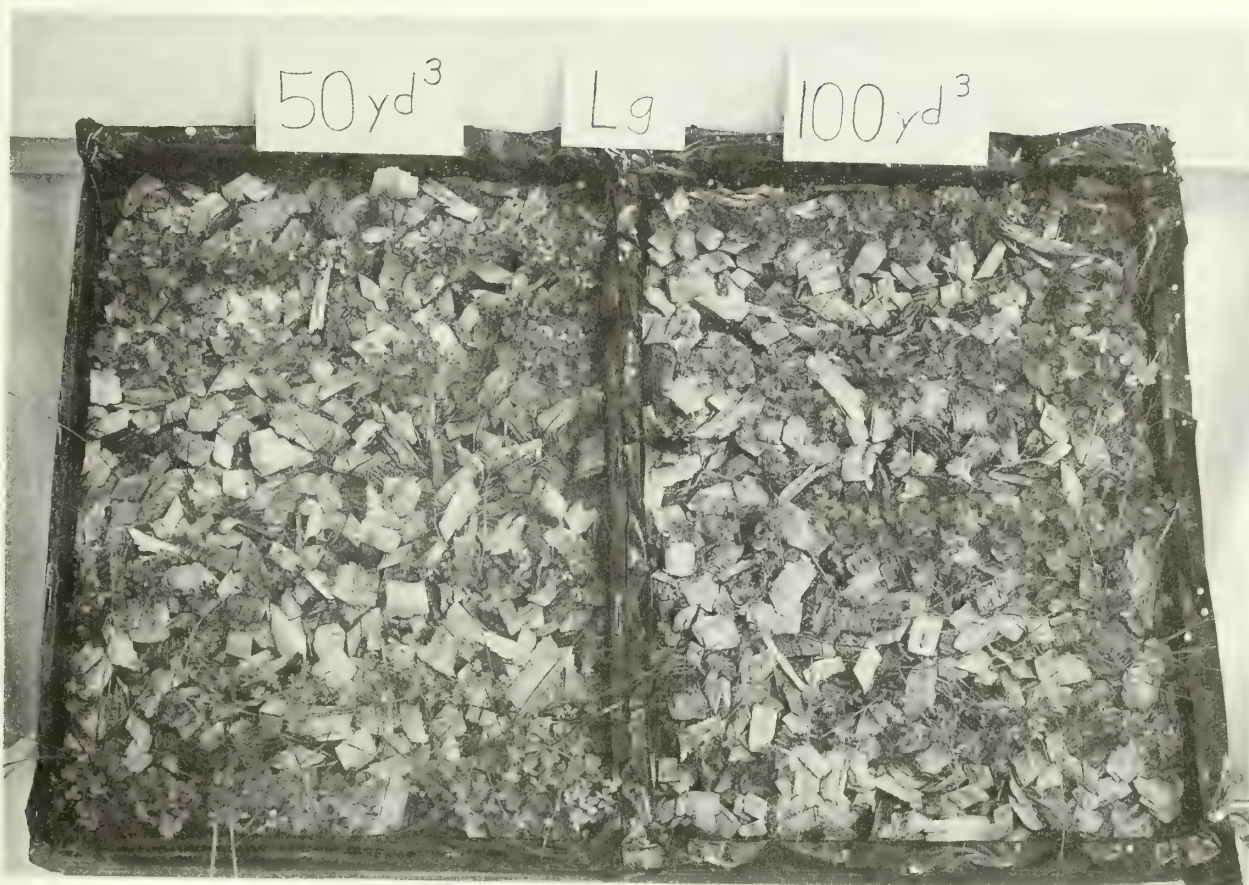


Figure 8.--Grass and legume emergence through large wood-chip mulch.

Compared to most of the grasses and legumes with smaller seeds, large-seeded species such as winter rye or sorghum will emerge through a greater thickness of mulch. Mulch depths of 1 inch or more have been used to cover large seeds. In a greenhouse study, it was found that bark mulch at rates of 50 to 100 cubic yards per acre ($\frac{3}{8}$ to $\frac{3}{4}$ inch in depth) will have little adverse effect on the emergence of most grasses and legume species. At rates greater than 100 cubic yards per acre, emergence of most species will be reduced (Fig. 9).

In general, light applications of cover mulch are more desirable than heavy applications. However, if application is too light, the result is little or no improvement in soil protection, seed germination, and ground cover. Too much mulch may smother seedlings by intercepting all light or by forming a physical barrier that seedlings cannot penetrate. Heavy applications may prevent full circulation of the air which can lead to composting. The heat generated from composting kills the seed and prevents seedling growth.

Erosion Control

When mulch is to be used alone as a temporary erosion control measure, the quantity of mulch needed at a specific site varies with the shape, slope, aspect, and roughness of the mine soil surface. Thicker applications are usually needed on bare soils, in drainage ways, on topsoil stockpiles, or during the dormant season when seeding is not practical.

The mulch should be deep enough to protect and hold the soil surface. Increasing rate usually gives increased protection. So, on steep slopes, mulch is usually applied to a depth of 2 to 4 inches to satisfy stabilization needs. High rates of mulch provide little additional reduction in runoff flow but give greater surface protection from raindrop impact.

Crop residues applied at rates of 1.5 to 4 tons per acre on agricultural soils reduce erosion. Wheat straw applied at 2 tons per acre on a 20 percent slope decreased runoff velocity by approximately two-thirds or from 0.08 foot per second to 0.03 foot per second. Runoff velocity for a $\frac{1}{2}$ ton per acre application is about half that for no mulch. Lower mulch rates effectively reduce erosion of fine sand but not silt-size particles. Although smaller rates provide lesser surface protection, they still help.

Plant Mulch

Heavier mulch application rates are required for plants than for seed cover to keep soils cooler for better woody plant growth and to control weed growth. For example, mulches for individual shrub or tree plantings and group or row plantings are usually applied from 4 to 6 inches deep.

The depth or thickness of the mulch to be applied will depend on the kind of mulch and the type of soil. Fine materials have better insulation properties than coarse materials, but when applied in a heavy layer, can affect aeration. When this happens, plants suffer. Thus, a mulch of sawdust should not be applied as thick as hay or bark. Additionally, a thicker layer of mulch can be applied to a light sandy soil than to a heavy clay soil. It is always necessary for air to reach the roots in the soil.

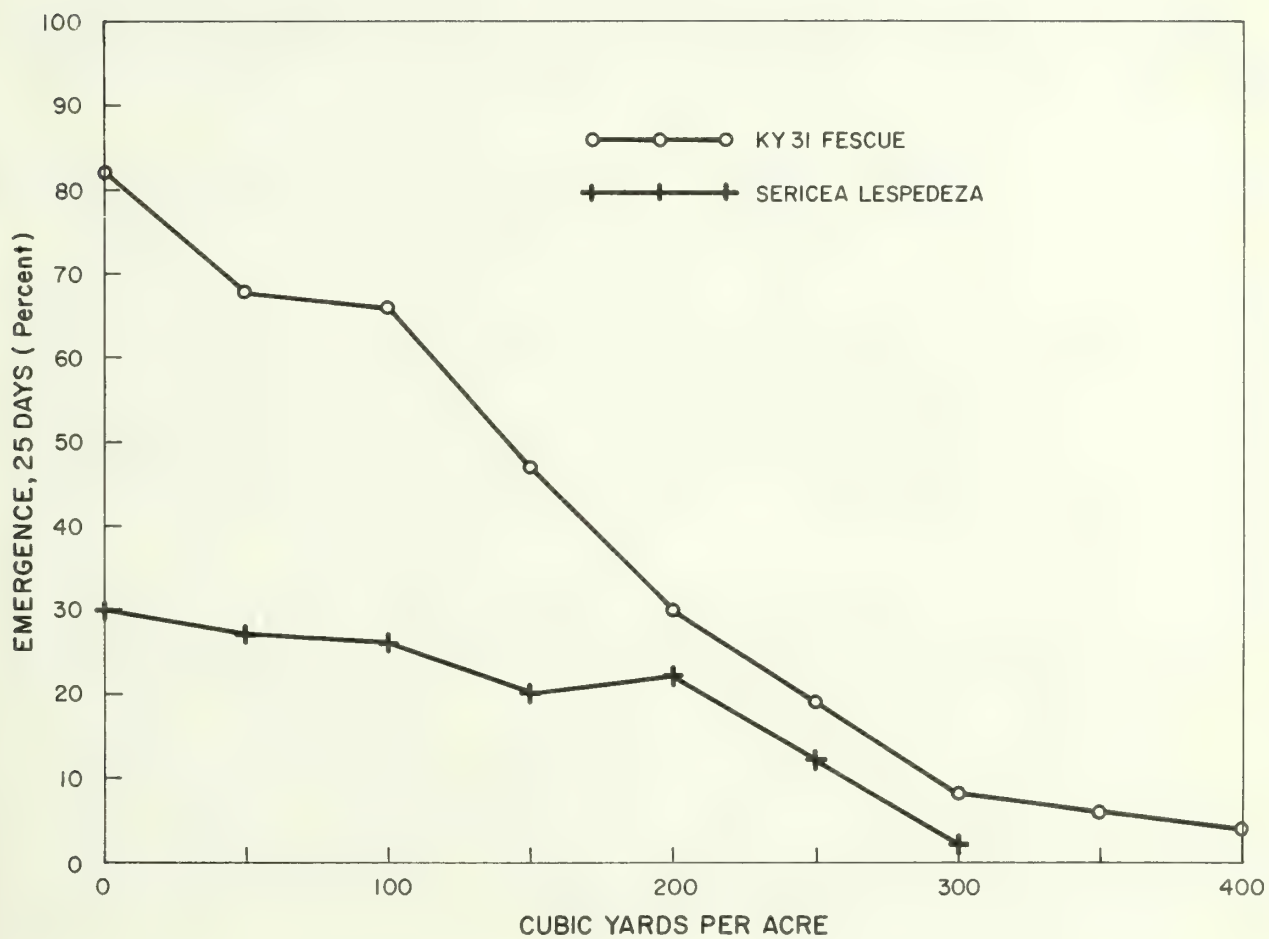


Figure 9.--Effects of rate of hardwood bark mulch on emergence of KY-31 fescue and Sericea lespedeza.

Site Conditions

Differences in site conditions, such as aspect, slope, weather patterns, and seasonal climatic variations, have an influence in determining a range of effective mulches and application rates. Aspect affects the choice of mulch color and dictates depth of application. The color and uniformity of mulch depth are critical because they have varying effects on establishment and growth of vegetation.

Adverse effects are usually related to seasonal variations in moisture and temperature. Because of this, mulch rates must vary. A site with a north-facing slope usually requires less mulch for a particular purpose than a south-facing slope. In the spring on gentle north- and east-facing slopes, thin, light applications of a dark-colored material may be necessary to raise surface temperatures to speed up germination, but at the same time must be heavy enough to protect the soil surface and slope from seasonal precipitation.

If conditions are severe, such as those frequently encountered on harsh sites, steep slopes, or south- and west-facing slopes, mulching rates are usually increased. In summer seeding on south and west slopes, heavy rates of light-colored material may be necessary to reflect solar radiation, to reduce evaporation, and to lower midafternoon temperatures that affect seed mortality and optimum plant growth. In the fall and winter, heavy applications of dark-colored material may be necessary to insulate soils and plants subject to frost heaving. Different mulch colors and rates are usually associated with north and south slopes, long and short slopes, and steep and moderate to level areas. For example, 30 cubic yards per acre of bark mulch would be used on a gentle, cool slope, while 50 cubic yards per acre might be necessary on steep, hot slopes.

Time of Application

Mulching materials can be applied at any season of the year depending on conditions of minesoil and weather at time of treatment and the intended purpose for which mulch is being applied. Usually mulch is spread immediately after seed and fertilizer have been applied, unless it is part of a hydroseeding operation.

Under most circumstances, it is essential that seeding and mulching take place shortly after the earth-moving and grading process so that both the actual disturbed area and the length of time it is exposed are kept to a minimum. If reclamation takes place at a time when seeding is least desirable (summer, late fall, and winter), mulches may be used to temporarily stabilize the soil until seeding can be done at a more favorable time.

Climate and Soil Conditions

The temperature and amount of rainfall at time of application will affect site conditions and influence the efficiency of the mulch material. Thus, sensitive field operations must be scheduled according to local weather patterns and conditions before, during, and after application.

In some areas, adverse weather and soil conditions may hinder access and on-site travel. To spread solid or liquid mulches, soils must be dry enough to support machinery and avoid soil compaction. In early spring, the ground is often too wet; mud can impede the operations of both seeding and mulching. Mulching can be done in the spring after the immediate surface soil has dried out.

Spreading of animal, municipal, and industrial sewage wastes should be avoided when runoff or leaching potential is high. Even though wet ground does not interfere with liquid application, the extra water could result in greater nutrient leaching and runoff losses.

Caution should be used when applying mulches to steep frozen or snow-covered ground. When applied under conditions leading to maximum spring snowmelt runoff, large amounts of organic materials or potential pollution can be transported from the land.

Wind direction and velocity can be limiting factors in sprinkler or spray and blower applications. They can cause uneven surface coverage and carry dust, mist, or unpleasant odors from material into areas of habitation.

Mulch Use and Seasons

Moisture and temperature regimes dictate the proper planting and mulching season and strongly influence results of mulching. Mulching for soil protection and seed cover should be scheduled so that moisture and temperature conditions are sufficient to germinate the seed and maintain seedling growth before adverse conditions occur. In addition, the application of mulch can extend the seeding season and make more effective use of existing and future moisture. To do the most good, mulches should be applied well in advance of spring rains, active weed growth, and summer drought.

If the intended use of the mulch is primarily for erosion control, proper timing of mulch application depends on the potential for loss of soil. Logically, then it will be timed to most benefit soil surface protection.

Materials used as plant mulches should be applied before active weed growth starts. If allowed to gain a strong foothold, weeds rob the plants of needed light, moisture, and nutrients. In summer applications, modifying the environment is most important because of the need to provide weed control, insulation, and shading. Applications in conjunction with fall planting of tree seedlings should be done well before the ground freezes. This will avoid alternate freezing and thawing that often results in seedlings being heaved out of the ground.

The proper time for seeding, planting, and mulching will vary from one region to another in the East and with the species to be planted. In some areas, there are several appropriate times for seeding and planting. The advantages and disadvantages of these planting periods should be known.

From a moisture and temperature standpoint, April, May, June, and late August, September, and October are the best times to seed and mulch. In most regions, weather patterns favor early spring seeding for cool-season species; fall seeding may produce the greatest success in other areas. For example, in western Kentucky, fall seedings are more successful than spring seedings because spring sown plants sometimes drought out during late spring and early summer. Early to midspring is normally the best time to sow perennial and some annual warm season species. Midspring to early summer is the best time for seeding most summer annuals. For example, spring seeding period in Illinois may extend from about March 15 to May 1 but in Alabama it may be February 1 to March 15. Similarly, recommended dates for late-summer and fall seeding are July 15 to August 20 in Pennsylvania, whereas August 15 to October 15 is suggested in Kentucky. Recommendation for best seeding and mulching dates in a given region can be obtained from local farmers and agricultural service agencies.

In areas with hot, dry summers, seeding in late spring and summer can be risky and is not recommended unless the area is mulched. In these areas, materials and rates superior for conserving moisture and moderating high air and soil temperatures are used to enhance germination and the establishment of seedlings.

In some regions, summer rainfall is usually sufficient to establish warm season annuals in late spring to midsummer without the benefit of mulch. Occasionally, summer precipitation is adequate for establishment of cool and warm season perennial species as well. Thus, where mining is completed in late spring and summer and the site is ready for reclamation, it should be seeded and mulched as soon as possible after grading is completed.

In late summer, it is desirable to mulch and establish sound vegetative cover before the fall rainy season or before winter to avoid soil and seed losses. In the fall, applications provide cold-weather protection with major influence on temperature and erosion control in winter and spring. Prolonged soil stabilization during winter is imperative since protective vegetative cover is not likely to be attained until spring. Winter mulches must be resistant to hard freezing and thawing conditions. Winter seeding is not required or recommended, though mulching areas that are ready for seeding may help control erosion during the winter. Adverse weather and spoil conditions, however, may hinder access and travel on mined areas.

Application Method

Uniform application of the mulch is critical to effect complete and even vegetation. Incorrect rates and distribution of the mulch material can impair the soil surface, delay seed germination and development, degrade the quality of surface and ground water, and evoke nuisance complaints from neighboring property owners.

Organic materials should be placed on soils in accordance with sound locally approved soil and water conservation practices. Such practices minimize the extent to which components of the material enter surface and ground water. They also minimize odors and provide for application to soils that will benefit the most.

Methods of mulch application vary depending on form of mulch material and type of equipment and labor available. The method of application chosen depends on whether the mulch is fibrous, solid, or liquid as well as on its particle size, weight, and composition.

Uniform distribution at the desired rate and depth is essential. Poor distribution may impair seedling growth or leave part of the surface inadequately protected. Depth is somewhat difficult to control because of uneven surfaces. However, an absolute even depth of mulch is not necessary as long as an average depth is obtained over the site. Mulching rates should be determined before the mulching operation and the equipment carefully calibrated to achieve the desired results. Commercial fiber mulches are often dyed with nontoxic fugitive green dye so that they are plainly visible when applied, aiding the operator in obtaining uniform coverage.

Currently, mulches are spread manually and mechanically with either of three spreading mechanisms: rotary, pneumatic, and hydraulic. All three mechanical application systems can be used in spreading various fibers, though solids are usually applied with a rotary spreader or pneumatic blower and some fibers and liquids with hydraulic spray. All types of mulch can be spread by hand.

Manual Application

Spreading or broadcasting mulch by hand is generally used in hard-to-reach, small (1 to 2 acre) areas, on harsh sites or steep slopes beyond the reach of a blower or hydraulic spray; and around trees and shrubs. The method is difficult, tedious, time-consuming, and costly even on small areas.

It is difficult to spread fiber evenly by hand, though leaves may be spread easily. Unchopped fiber spread by hand remains in place and is more effective than chopped, yet the manual labor required for such spreading is costly.

Mechanical Application

Many types of mulch material are applied uniformly by mechanical means. Physical characteristics of the mulch may be such that specialized equipment must be used if it is to be spread efficiently and economically. Rotary pneumatic or hydraulic application requires products that are uniform in size and preferably free of trash, dirt, and dust.

Rotary Spreaders.--Mulching with rotary spreaders is common and involves the application of dry, fibrous and heavy, solid mulch by using a combination of conveyors, augers, rotary beaters, paddles, flails or centrifugal bladed disks, or spinners to broadcast the mulch to the rear or to one side of the machine. Lime/fertilizer spreaders, municipal spreaders, manure spreaders, modified stack processors, and tub grinders are conventional and modified equipment available in this category. Rotary spreaders are driven or pulled and work well on benches, terraces, and level or moderately rolling terrain adaptable to typical agricultural implements. Usually only two people are required on a rotary spreader operation. A third may be necessary if the mulch has to be tacked.

Pneumatic Spreaders.--This method uses an airstream to dispense mulch. Dry fibers or solid mulch materials are blown out of a discharge chute onto an area using air pressure generated by a motor-driven, high-pressure, paddle-wheel fan. An impactor is provided on some machines as an additional force to more efficiently propel heavier material. Some machines are equipped to spray a chemical adhesive (tackifier) on the mulch as it leaves the discharge spout.

Fiber is spread more easily by blower than by hand. A blower shreds, cuts, and evenly spreads or scatters fibrous material. The mulch lies down in closer contact with the soil than does hand-spread fiber. A fine-stemmed, baled, fiber mulch is preferable to a loose mulch for pneumatic spreading.

Wood fiber or cellulose can be applied with a blower but application in this manner leaves much to be desired. Leaves even when damp can be spread with a pneumatic spreader. Power mulchers and the Estes spreader are conventional and modified equipment available in this category.

Pneumatic spreaders provide the ability to cover inaccessible or steep slopes. They are drawn or driven along a road, terrace, or bench above or below the slope to be treated. They enable mulching of steep slopes without the water required for hydromulching.

Four people are usually required to operate pneumatic spreaders efficiently with a possible fifth person needed when it is necessary to tack the mulch.

Hydraulic Spreader.--Hydraulic spreaders are used to apply wood fiber and cellulose. Tank trucks with gravity or pumped discharge and various forms of sprinkler/irrigation are used to apply slurry and liquid sewage wastes.

Spray applications are used most successfully with wood fiber or cellulose mulches applied with a hydraulic seeder, more commonly called a hydroseeder or hydromulcher. The main advantage of the hydraulic spray method is that mulch can be applied to areas that cannot be easily reached by other methods. The spreading distance is as much as 200 feet from the machine depending on efficiency of the machine and wind conditions.

The system is popular because of ease of application and because all materials needed for revegetation can be applied in one pass over the area.

Disadvantages of the hydraulic spray equipment are that only a relatively small area can be treated with each load of material and a source of water must be readily available near the mulching job. A considerable amount of time may be required in transporting or pumping water.

Liquid and slurry sewage waste are applied by self-propelled sprinkler irrigation equipment, such as a center pivot or a portable or traveling gun, which has a single large nozzle (3/4 inch to 2 inch orifice) with 80 to 100 psi pressure. With the traveling gun system, a large single sprinkler on a carriage is winched across the area, pulling a flexible hose through which sludge is pumped. An aerosol drift problem may occur with high pressure sprinkler systems. Spray irrigation may involve the construction of distribution pipe lines (either stationary or movable), the installation of pumping equipment, and time-cycle devices.

Mulch Anchoring

It is essential that some mulches, such as cereal crop straws, hay, leaves, wood fiber and cellulose, and other lightweight fiber materials, be anchored to the soil surface to assure protection of the soil. Some can be anchored as they are being applied. Where this is not possible, they should be anchored with a tackifier, such as asphalt, immediately after placement to minimize loss or movement. Coarser aggregates such as shredded bark have interlocking pieces that have a tendency to stay in place even on steep slopes.

Size of area, mulch material, cost, and effective life of required treatment should determine the anchoring method to be used. Whatever method is selected, it should effectively hold the mulch in place until vegetation takes over. The basic methods of anchoring mulches are manual, mechanical, and chemical.

Manual Anchoring

Manual anchoring is most applicable on small or critically sloping areas. It involves manually tying the mulch down with stakes or pegs, twine, string netting, or wire mesh. If stakes are used, they are driven usually on five foot centers with twine strung between stakes to form square, diamond, or cross patterns over the surface of the mulch. A variety of nets and mesh have been used including jute, baling wire, wire poultry netting, concrete reinforcing wire, chain link fencing, plastic fabrics, and twisted woven kraft paper (Fig. 10). Nets and mesh should be anchored at enough points to prevent material from curling or whipping in a wind.

Mechanical Anchoring

Mechanical anchoring is the pressing of a fiber mulch into the soil by crimping, discing, or rolling. The average length of blown mulch fiber should be 6 inches and incorporated to a depth of 1-1/2 to 3 inches, which is sufficient to anchor but not bury it. Properly placed fibers should create a stubble effect that provides an excellent obstruction for wind saltation and surface flow (Fig. 11). Straw, unless crimped, tends to perch rather than bind with the soil, allowing rilling even on gentle slopes. Fiber crop residue used for mulch should be new and pliable because excessively dry or rotten mulch is easily broken or cut in two.

Machines for anchoring operate most efficiently on relatively level or moderately rolling land with slopes less than 3:1. On steep slopes, where machines are not suitable, mulch should be anchored with nets, mesh, or a chemical tackifier.

Crimping is accomplished with a specially designed crimper or with a conventional farm disc. These machines work best if the soil has been scarified to a depth of 4 to 6 inches during seedbed preparation because the blunt notched disks will not penetrate hard soil.

Rolling or punching is done with a specially designed pronged roller. A conventional sheeps-foot roller may be used on light soils. Punching may not be as effective as crimping because of the staggered arrangement of punched mulch compared to the "whisker dams" made by crimping.



Figure 10.--Plastic netting.



Figure 11.--Straw mulch anchored by crimping.

Chemical Tackifier

Tackifiers are organic and inorganic chemical products applied in water solutions to lightweight mulches to hold them in place. Chemical tackifiers can be added to the mulch as it is being applied. Adhesive injectors can be mounted at the mouth of the discharge chute to coat the mulch as it is ejected. Alternately, hydraulic sprayers can be used in a separate operation to cover the mulch after it is on the ground.

Numerous chemical stabilizers are available. However, there is insufficient knowledge about the comparative value of different products and about the most effective application rates for specific materials. Two broad classes of chemical stabilizers are recommended as tackifiers: polyvinyl acetate emulsions and acrylic copolymer emulsions. Recommended application rates are 25 to 50 gallons per acre. A dilution rate of 1:10 to 1:20 (1 part stabilizer to 9 or 19 parts water) is suggested.

The most commonly used chemical tackifier in the Eastern United States is asphalt emulsion at a rate of 600 to 1,200 gallons per acre. Caution must be exercised in using asphalt because it may retard germination and lower seedling start. Some plants react negatively to asphalt, while others react positively. Asphalt softens in hot weather and can be a sticky nuisance if allowed to drift onto traffic areas. Its black color helps increase soil temperature which may help to encourage growth in cool weather. Asphalt adhesives for application with mulch are usually liquid asphalt conforming to American Society for Testing and Materials (ASTM) Specifications D2028, designation RC-70 or emulsified asphalt conforming to ASTM Specifications D-77, grade SS-1. The specifications used by the Soil Conservation Service are:

1. Liquid asphalt rapid curing (RC-70, RC-250, or RC-800) or medium curing (MC-250 or MC-800). Apply 0.1 gallons per square yard.
2. Emulsified asphalt (SS-1, SSk, SM-K, MS-2, RS-1, RS-2, RS-2K, or RS-3K). Apply 0.04 gallons per square yard.

Rapid setting (RS) is formulated for curing in approximately 24 hours. Slow setting (SS) is formulated to allow adequate working time during dry hot weather. A higher number in the formula indicates a heavier residue. Emulsion can be applied either as a separate spray over the mulch or simultaneously with the mulch using the injection method. Some materials are applied from the top of a slope down with blowers equipped to spray a chemical tack on the mulch as it is being discharged. Application from the toe of a slope upward can create small dams that pond water on the surface of the mulch, causing some slumping, especially where the mulch helped maintain moisture at field capacity. Asphalt is nonporous, causing surface water to run off, but conserves moisture underneath it.

Chemical stabilizers also are used in combination with wood fiber and wood cellulose mulches more frequently than stabilizer alone. Assuredly, site protection obtained with low rates of the combined material is comparable to that obtained with high rates of either product used alone. A combination recommended and used in some eastern states is: 50 gallons per acre of stabilizer mixed with a minimum of 500 pounds per acre of wood fiber or wood cellulose.

Because they can be applied with a hydroseeder, chemical stabilizers have an advantage for tacking mulches on long steep slopes and other hard-to-reach places.

It is not feasible here to list all of the chemical tackifier products presumably available or to rate their comparative values. They are costly and usually require more precise preparation and procedural placement control than mulches. For those interested in using chemical tackifiers, advice should be sought from research reports on their use or from reclamation companies, highway departments, and conservation agencies that have had experience with their use. Sales promotions are not always reliable sources of information.

Fiber.--Wood fiber or wood cellulose alone or premixed with chemical tackifier can be used as a short-term adhesive. The strength of the bond and the effective life of the treatment depend on the amount of the tackifier applied; the higher the rate, the greater the effectiveness.

In experiments, a straw mulch tacked with 700 pounds per acre of wood-fiber mulch by the hydro method served as a good mulching combination with better results than many of the binder or tacking agents (Fig. 12). Additionally, a very fibrous type of shredded hardwood bark mulch applied and held in place with emulsified asphalt may produce a mulch equal in effectiveness to sodding or jute matting for controlling erosion.

Application Equipment

A variety of equipment has been developed or adapted to aid mulching and anchoring. Conventional implements are used in normal operations, and specialized equipment is required on large areas and steep slopes. Usually, heavy-duty implements will be more useful and require less maintenance than light- and medium-duty machinery.

In selecting equipment, consideration must be given to the type of terrain to be covered, the size of the area, the cost of labor, and support equipment needed to service and operate conventional application equipment efficiently. For example, wheel-type equipment cannot be used on very steep slopes (3:1 or less). Therefore, the equipment selected must be adaptable to a travelway, a bench, or have the spray capability and range to cover hard-to-reach areas. Good mulching and revegetation jobs are achieved through use of the right equipment and not by attempting to economize with makeshift equipment. The increased success obtained will more than offset equipment costs.

Equipment companies continually are redesigning and modifying standard equipment or developing new equipment. Researchers, as well as mining and reclamation companies, continue to develop equipment designed to meet specific reclamation needs.

As an aid in planning mulching treatments and selecting suitable equipment, the most recent information on the following equipment designed or adapted for preparing and applying mulch has been assembled:



Figure 12.--Hydromulch fibers over straw mulch.

Spreaders

Rotary

- Lime/fertilizer/sludge
- Manure spreader
- Modified stack processor
- Roto-grind mulcher

Pneumatic

- Power mulcher
- Estes blower/impactor

Hydraulic

- Seeder/mulcher
- Tank truck
- Irrigation sprinkler systems

Anchoring

Manual

- Stakes
- Twine
- Netting
- Wire mesh

Mechanical

- Disc
- Krimper-Finn
- Roller

Chemical

- Power mulcher
- Hydraulic sprayer

Essential facts are provided on the structure and operation of equipment, including its function, description, techniques for use, capabilities and limitations, general specifications, labor and equipment requirements, and sources of supply. Most of the equipment described and illustrated is commercially available. In some areas, various equipment may be available on a rental basis.

Fertilizer Spreader

Function.--Fertilizer spreaders distribute dry solid material over large, level, or moderately rolling terrain. They have large capacities and adjust for a variety of application rates. Materials that can be spread with this equipment are lime, fertilizer, shredded or chunk bark, sawdust, wood chips, corncobs, composted municipal wastes, or dewatered sludge.

Description.--Fertilizer spreaders are usually mounted on trailers, trucks, or high flotation equipment. They have large hoppers with sloped sides. The sides converge on a steel mesh or rubber conveyor belt that moves the material to the rear of the hopper and drops it onto one or two rotating, bladed disks or spinners. The spinners and conveyor belt are usually powered hydraulically or with power-take-off (PTO) from a tractor. The conveyor belt is sometimes wheel-driven. Agitators placed above the conveyor belt ensure a continuous flow of material (Fig. 13).

Techniques.--The fertilizer spreaders are driven or pulled over the area to be treated. The application rate is controlled by the size of the rear hopper opening or the speed of the conveyor belt. The spinner is kept constant for even distribution over the swath.

Capabilities.--Fertilizer spreaders have large capacities and are adjustable over a variety of spreading rates. Most types of dry amendments can be spread with them.

Limitations.--Fertilizer spreaders are not suited to rough or very steep land. They are most useful where amendments are spread rapidly over large areas.

Specifications.--High flotation or truck mounted

Pattern width: 24 to 60 feet

Hopper capacity: 5 to 14 cubic yards; 5 to 17 tons

Labor and Equipment.--This machine requires one person to operate the prime mover, a second to operate front-end loader for loading material on site, and a third when mulch requires tacking.

Availability.--High flotation or truck-mounted:

Ag chem Equipment Co.
4900 Viking Dr.
Minneapolis, MN 55435
(612)835-2476

Big Wheels, Inc.
Box 113
Paxton, IL 60957
(217)379-2369

Dempster Industries, Inc.
Box 848
Beatrice, NE 68310
(402)223-4026

Henderson Manufacturing Co.
Box 40
Manchester, IA 52057
(319)927-2828



Figure 13.--Truck-mounted fertilizer spreader.

Highway Equipment Co.
616 D Avenue NW
Cedar Rapids, IA 52405
(319)363-8281

John Blue Co.
Box 1607
Huntsville, AL 35807
(205)536-5581

Lakeside Truck Body Co.
Box 1104
Turlock, CA 95380
(209)632-7501

Rickel Manufacturing Co.
Box 626
Salina, KS 67401
(913)825-1631

Tryco Manufacturing Co.
Box 1277
Decatur, IL 62525
(217)428-0901

Tyler Division
TCI, Inc.
Benson, MN 56215
(612)843-3333

Wilmar Manufacturing Co.
Box 957
Wilmar, MN 56201
(612)235-0767

Manure Spreader

Function.--Manure spreaders are used to distribute heavy solids over an area.

Description.--Manure spreaders are large, open trailers or trucks with conveyor beds. The spreading mechanisms located at the rear of the spreaders consist of beaters, paddles, or flails which rotate at moderate speeds forcibly ejecting the material. The spreading mechanisms and conveyor beds are usually powered through PTO attachments. Auxiliary beaters are often located above the spreading mechanisms to aid the flow of material through the spreaders. A modified manure spreader has been specially developed to distribute mulch over surface-mined land. Blueprints for modifying the spreader are available from the Equipment Development Center, U.S. Forest Service, Missoula, Montana (Figs. 14 and 15).

Techniques.--The spreaders are towed or driven over the areas to be treated. The conveyor moves the material to the rear of the spreaders where it is ejected by the rotating beaters, paddles, or flails. Discharge rates can be varied by adjusting the speed of the conveyor bed.

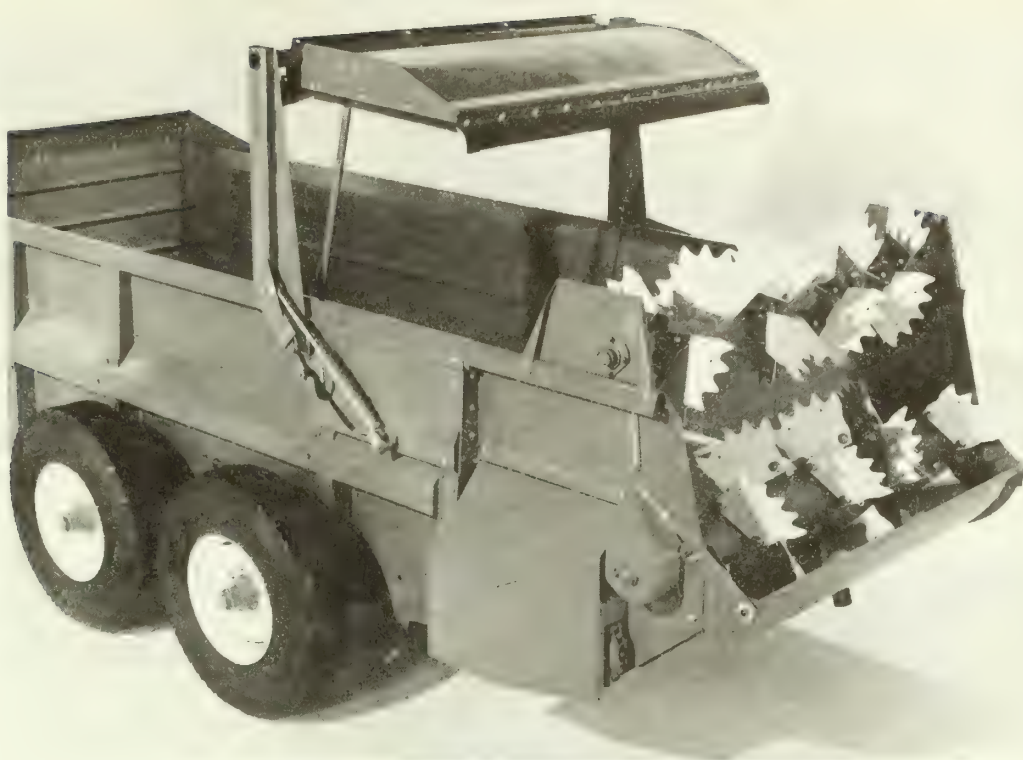


Figure 14.--Standard manure spreader.

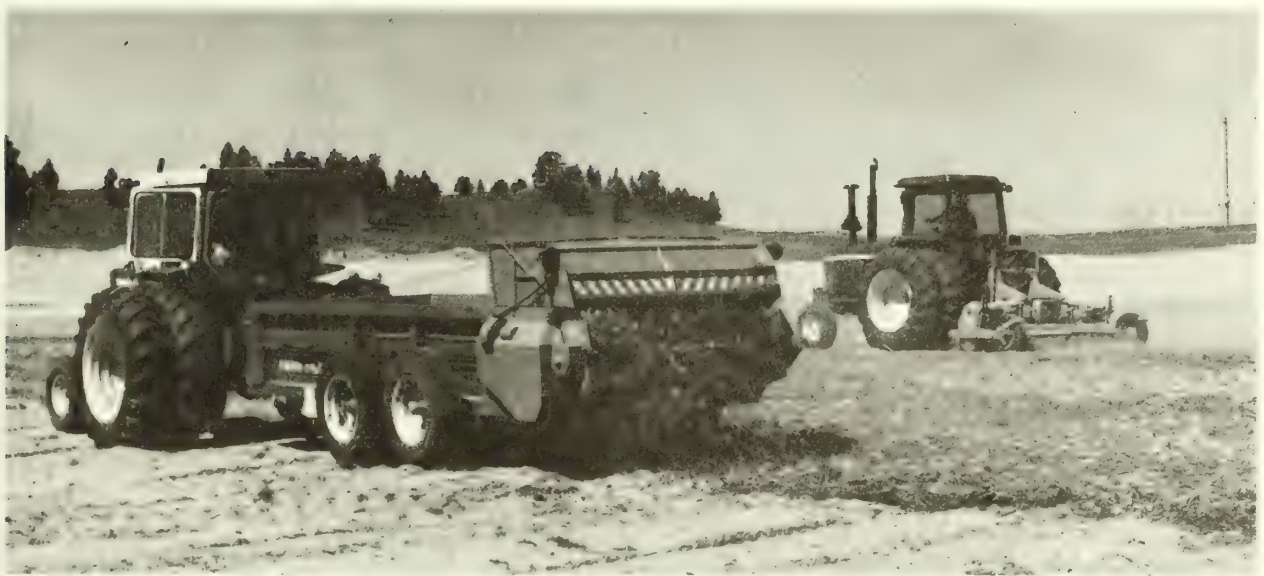


Figure 15.--Manure spreader modified to apply straw mulch.

Capabilities.---Manure spreaders can handle and distribute almost any type of mulch, including animal wastes, straw, hay, caked sewage sludge, leaves, sawdust, bark, and wood chips.

Limitations.---The operation of manure spreaders is limited to gently to moderately sloping terrain. Uncomposted manure is difficult to distribute evenly. Baled fiber tends to fall in bunches unless it is cut or shredded for scattering.

Specifications.

Capacity: 64 to 360 cubic feet (2.8 to 18 tons) level full

Overall width: 6.5 to 11 feet

Power requirements (drawbar): 30 horse power, minimum

Labor and Equipment.---This machine requires one person to operate the prime mover. A supply truck and driver can be used to deliver material to the machine in the field.

Availability.

AVCO

New Idea Farm Equipment
420 South First Street
Coldwater, OH 45828
(419)678-5311

Big Wheels, Inc.

Box 113
Paxton, IL 60957
(217)379-2369

Blair Manufacturing Co.

929 East Washington
Blair, NB 68008
(402)426-2151

Deere and Co.

John Deere Road
Moline, IL 61265
(309)752-8000

Du-Al Manufacturing Co.

1000 West Cherokee Street
Sioux Falls, S D 57104
(605)336-3869

Farm Hand, Inc.

525 15th Avenue South
Hopkins, MN 55343
(613)938-7651

Ford Tractor Operations
2500 East Maple Road
Troy, MI 48084
(313)643-2000

Gehl Company
143 East Water Street
West Bend, WI 53095
(414)334-9461

Hawk Bilt Company
402 East 6th Street
Vinton, IA 52349
(319)472-2313

International Harvester Co.
Agricultural Equipment Division
401 North Michigan Avenue
Chicago, IL 60611
(312)836-3874

Schultz Manufacturing Co.
Box 388
Waterloo, IA 50704

Schwartz Manufacturing Co.
Box 248
Lester Prairie, MN 55354

Sperry New Holland
500 Diller Avenue
New Holland, PA 17557
(717)354-1121

United Farm Tools, Inc.
Box 9175
South Charleston, W V 25309
(304)768-8221

Modified Mulch Spreader:

Drawings (No. 611) and information can be obtained from:

USDA
Equipment Development Center
Bldg. 1, Fort Missoula
Missoula, MT 59801
(406)329-3157
FTS 585-3157

Modified Stak Processor

Function.--A Hesston Stak Processor modified with a flail device is used to distribute straw or hay mulch from 1,500-pound round bales.

Description.--The Stak Processor was designed to lift, transport, and shred large round bales of hay and to distribute it in windrows for cattle feed. The implement consists of a four-tine, hydraulic bale-pickup and a shredder and auger powered by PTO.

The modification or MacFarland flail consists of a standard hydraulic motor with four reinforced rubber-belt flails and a stabilizer mounting bracket attached underneath the side opening of the Stak Processor. The flail hydraulics are independent of the bale pickup and allow the flail speed and direction of rotation to be controlled from the tractor (Figs. 16 and 17).

Techniques.--The pickup tines slide under the bale and are tilted up, forcing the bale into the shredders. The shredders break apart the compacted straw or hay and deliver it to the auger. The auger forces the material out the side of the machine into the MacFarland flail.

The flails intercept the mulch material from the Stak Processor discharge and distribute it over a wide area. Flail speed should vary inversely to the tractor speed for uniform distribution. Flail direction is clockwise, except when strong winds are blowing from the rear of the unit or into the discharge chute.

Capabilities.--Picking up and distributing large round bales becomes a simple, one person task with the modified Stak Processor. The speed and direction control of the flail unit allows uniform distribution of mulch under most conditions.

Limitations.--The modified Stak Processor is not suited for steep or rough terrain.

Specifications.

Capacity: 3,000 pounds

Flail speed: 100 to 1,000 revolutions per minute

Power-take-off (PTO) speed: 540 revolutions per minute

Power requirements (drawbar): 40 horse power minimum

Labor and Equipment.--One person is required to operate the prime mover for the machine.

Availability.

Stak Processor:

Hesston Corporation
Box 788
Hesston, KS 67062
(316)327-4000



Figure 16.--Hesston Stak Processor with MacFarland flail to distribute straw mulch from round bales.



Figure 17.--MacFarland flail.

Western Energy Co.
Box 67
Colstrip, MT 59232
(406)748-2366

Tub Grinder--Mulchmaster

Function.--The Roto Grind Mulchmaster spreader applies wet or dry fiber and solid mulch, such as large (1,500 pounds) round or standard square hay or straw bales, and other types of crop residue, shredded or chunk bark, wood chips, or most any other organic material.

Description.--The Mulchmaster is a modified rotary tub grinder. A large tub-shaped hopper is mounted at the top of the machine over four sets of hammers mounted on a flywheel-type rotor. The hopper revolves, using prime mover hydraulics, and shoves the mulch material into the rotating hammers that tear the material apart and blow it out the discharge located on the left side of the machine. An adjustable riser works in conjunction with the hammers to control the amount of material that is discharged per revolution of the hopper. The direction of flow of material can be controlled upward or downward by two adjustable plates on the discharge (Figs. 18 and 19).

Techniques.--The Mulchmaster is towed over the area to be treated. Loose material or bales of mulch are dumped into the hopper with a front-end loader. The rotary tub feeds the material into the mulching rotor where it is ejected by the rotating hammers. Ground speed of the unit, plus rotational speed of the tub and rate of flow, determine the amount of mulch applied per acre.

Capabilities.--The Mulchmaster spreader is useful for highway roadside stabilization and surface-mine reclamation. The spreader is designed to efficiently distribute almost any type of wet or dry organic material.

Limitations.--The Mulchmaster spreader is limited to accessible areas and to moderate slopes. Wet material can be spread but uses more horse power and tends to bunch slightly. A safety problem is presented when small foreign objects or chunks of hard material are ejected from the discharge at high velocity.

Specifications.

Capacity: Ranges from 5 to 20 tons per hour, depending on type of material, moisture content of material, horse power used, and speed of loading.

Hammer speed: 1,000 revolutions per minute

Tub speed: 0 to 9 revolutions per minute

Power requirements: 80 horse power or more; PTO speed 1,000 revolutions per minute

Spread rates: 5 to 20 tons per hour or 20 to 40 acres per day



Figure 18.--Mulchmaster spreading mulch on snow to show spreading pattern.



Figure 19.--Roto Grind Mulchmaster.

Spread distance: 60 to 70 feet

Labor and Equipment.--Two people are required for effective operation and probably a third where tacking mulch is necessary.

Availability.

Burrows Enterprises, Inc.
6340 West 10th St.
Greeley, CO 80631
(303)-353-3769

Power Mulchers

Function.--Power mulchers blow dry fiber mulch, mostly straw and hay, onto treatment areas.

Description.--A power mulcher blows dry fiber mulch with air pressure generated by a motor-driven, high-pressure fan. The mulcher has an adjustable-height loading chute with either gravity feed or variable-speed conveyor feed. The blower mechanism consists of rotary beaters to break up the mulch, a paddlewheel fan to generate pressure, and a discharge chute. The chute can rotate in a full circle horizontally and up to 70 degrees vertically (Fig. 20).

Techniques.--Bales of mulch are transported on the mulcher's prime mover and placed on the loading chute one at a time. They either slide or are conveyed into the chamber with the rotary beater. The rotary beater breaks the bales apart and separates the mulch fibers. The mulch fibers are then sucked into a fan and blown out the discharge chute directed toward the slope. An adhesive (tackifier) can be atomized in the airstream and combined with the mulch fibers.

Capabilities.--Power mulchers provide the ability to cover inaccessible slopes (both up and down) with self-attaching mulch from a nearby bench or road. The mulcher can use any long-fiber, dry mulch, but not all mulches produce similar results.

Limitations.--Small light materials, such as sawdust, are difficult to blow far and are subject to drift. Heavy materials such as large wood chips, chunk bark, or shredded bark will not carry far and tend to tear up the beater and fan mechanisms. An impactor is needed to propel heavy mulches.

Specifications.

Spread rates: To 15 tons per hour; about 40 acres in an 8 hour day

Spread distance: To 70 feet

Adhesive pump capacity: To 50 gallons per minute

Power ratings: 30 to 109 horse power

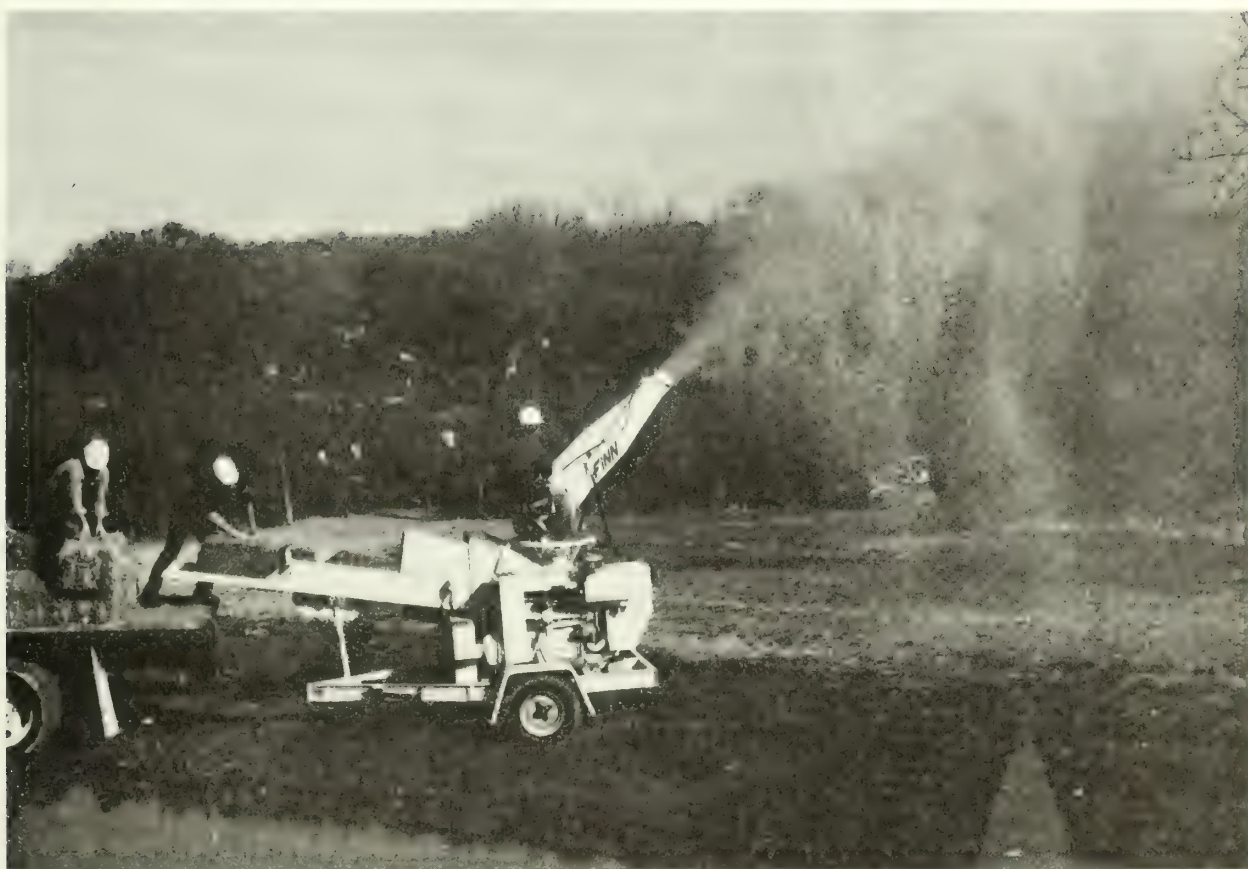


Figure 20.--Power mulcher spreading straw.

Labor and Equipment.--Four people are needed to efficiently operate a power mulcher--the mulcher operator, a prime-mover operator, supply-truck driver, and end-loader operator. A fifth person is needed where a machine is required to crimp the mulch into the soil, or when water trailer or asphalt emulsion trailer is needed for tackifier. This machine requires more manpower than truck-mounted blowers.

Availability.

Finn Equipment Co.
2525 Duck Creek Road
Cincinnati, OH 45208
(513)871-2529

Reinco
Box 584
Plainfield, NJ 07061
(201)755-0921

Estes Blower Spreader

Function.--The Estes blower spreader applies solid materials such as lime, fertilizer, shredded or chunk bark, sawdust, wood chips, corn cobs, or composted municipal wastes. The amendments or mulches, singly or in combination, can be blown 75 feet up or down a 60 degree slope and up to 125 feet horizontally.

Description.--The Estes blower spreader is a blower/impactor that attaches to the hopper of a large, truck-mounted rotary spreader. The conveyor within the hopper transports the amendments into a blower/impactor mechanism with a large fan driven by a separate gasoline engine. A hydraulic cylinder, operated from the cab, controls the vertical angle of the flow of the discharged materials. Spinners, such as those of most rotary spreaders, can accompany the Estes spreader to distribute amendments near the truck (Fig. 21).

Techniques.--The Estes blower spreader is driven along a road or terrace above or below the slope to be treated. The amendments are blown up or down slope from the truck. The hydraulic direction control allows adequate coverage of changing slopes. Application rates are determined by the speed of the truck and the blower speed. To fully cover an area, spinners are needed to spread close to the truck.

Capabilities.--The Estes blower spreader is useful for roadside stabilization or surface-mine reclamation. It enables liming, fertilizing, mulching, and seeding of steep slopes without water and without mechanical disturbance.

Limitations.--The Estes blower spreader is limited to accessible areas. The mouth of the blower discharge is located on the left side and cannot be rotated horizontally. Wind affects the distribution of light materials. Heavy materials tend to carry farther, resulting in uneven distribution of materials with different weights. A safety problem is presented when large chunks of hard material are ejected from the blower at high velocity.



Figure 21.--Estes spreader mounted on a truck hopper.

Specifications.

Spread width (blower spreads only on the left side of the vehicle):

Blower: 75 feet on 60 degree slope

Blower: 125 feet on level ground

Spinners: To 40 feet

Spread rate: 50 cubic yards per hour

Pay load: 15 to 17 cubic yards

Power rating: 56 horsepower

Labor and Equipment.--This machine requires two people for efficient operation, a spreader truck driver and front-end loader operator, and probably a third where tacking the mulch is required.

Availability.

Estes Equipment Inc.
Route 4, Bybee Road
Winchester, KY 40391
(606)-744-5900

Hydraulic Seeder-Mulcher

Function.--Hydraulic seeder-mulchers can apply seed, fertilizer, and soil amendments including wood fiber and cellulose mulch, in a hydraulic spray. They provide a method of seeding and mulching steep slopes without operating a prime mover on the slopes.

Description.--Hydraulic seeder-mulchers consist of a tank, a pump powered by a separate engine, and a discharge-nozzle assembly. The tanks are equipped with various types of agitators to assure uniform mixtures. Large centrifugal pumps can spray the mixtures up to 200 feet and have particle clearances of up to 1-1/2 inches. Interchangeable discharge nozzles provide a variety of spray patterns. The nozzle assemblies can rotate a full 360 degrees horizontally and from 120 to 180 degrees vertically to provide complete coverage. Hydraulic seeder-mulchers may be mounted on either a trailer or truck frame (Fig. 22).

Techniques.--The tank is filled with a slurry containing 3 to 6 percent solids by weight. The operator sprays the mixture over the area, controlling the spray pressure and volume. The hydraulic seeder-mulcher can be operated while stationary or moving. A separate hand-held hose is available for small-scale or spot treatments.

Capabilities.--Hydraulic seeding and mulching is a fast, efficient method of mulching steep, hard-to-reach areas. Application rates may be varied to suit conditions. Dyed wood fiber enables the operator to visually determine what areas have been covered.



Figure 22.--Truck-mounted hydraulic seeder-mulcher treating a slope.

Limitations.--Hydraulic seeding or mulching demands large amounts of water, which may not be readily available. Only a relatively small area (1 to 2 acres) can be treated with each load of material. It is preferable that seeding and mulching are done in separate operations so the seed are not held off the ground by the mulch fibers. Many seeds may be damaged by the agitators and pumps. When wood-cellulose fiber mulch is added to the slurry, the area covered by a single fill is reduced by 50 percent. Wood-cellulose fiber should contain no more than 10 percent moisture, air-dry weight basis.

Specifications.

Spray range:

20 to 200 feet

360 degrees horizontal rotation

120 to 160 degrees vertical travel

Spread rate: 3,000 gallons per hour

Tank capacity: 150 to 3,000 gallons

Pump capacity: 70 to 950 gallon per minute

Power ratings: 8 to 151 horsepower

Labor and Equipment.--At least four people are needed to operate this machine. A prime-mover operator, spray-nozzle operator, tank-truck operator, and fiber-supply truck driver.

Availability.

Bowie Industries
Box 931
Bowie, TX 76230
(817)872-2286

Finn Equipment Co.
2525 Duck Creek Road
Cincinnati, OH 45208
(513)871-2529

Reinco
Box 584
Plainfield, NJ 07061
(201)755-0921

Tank Truck

Function.---Commercial tank trucks and tank wagons spread slurry or liquid animal wastes, sewage sludge, and industrial wastes directly on the surface of the soil. The material may be absorbed directly by the soil and acted on by soil microorganisms.

Description.---Tank trucks consist of tank for the liquid with quick opening/closing valve and deflector plate to fan the slurry over a wide area. Usually, gravity discharge is used, but some commercial tanks can be pressurized or pumped. Tank systems may be mounted on regular trucks, trailers, or high-flotation equipment.

Techniques.---The tank truck or wagon with high flotation tires is driven or pulled across the area to be treated. The liquified waste is spread with either gravity flow or pressurized spray from the rear of the tank. The swaths are overlapped to ensure complete coverage. Application rates are determined by the speed of the truck and the discharge flow. With optional hydraulic hoist, the tank may be elevated for ease of complete emptying of liquids and semiliquids (slurries). On some trucks, leak-proof, full-opening rear doors facilitate tank cleaning, repair, or service. Tanks with pressure pumps can be driven along a road terrace or bench above or below the area or slope to be treated. The waste is sprayed over the area with discharge nozzles on the truck.

Capabilities.---Tank trucks or wagons spread liquified sewage wastes directly on the soil. The materials are not readily removed by surface winds or runoff. High-flotation equipment can be used on soft ground. Pressurized tanks permit steep slope treatment without mechanical disturbance.

Limitations.---Regulations may restrict or prohibit pressurized spraying in certain locations. Odor may be a nuisance when waste is not incorporated into the soil. Tanks with gravity discharge are limited to level or slightly rolling terrain. Equipment with high-flotation tires may have a restricted hauling range. Regular trucks and trailers can be used only on dry or grass-covered areas.

Specifications

Truck mounted and high flotation:

Tank capacities: 1,600 to 4,000 gallons

Tank diameters: 48 to 72 inches

Tank length: As long as necessary to obtain given capacity

Pressure/vacuum pump: High-speed, self-lubricating, air
or oil cooled

Auxiliary engine with two-way valve

Hydraulic pump and hoist control

Pattern width: 12-foot swath at speed of 10 miles per hour

Flotation tire: 15 pounds per square inch ground pressure

Trailer mounted:

Tank capacities:

Regular trailer: 500 to 3,300 gallons

Semitrailer: 4,600 to 6,000 gallons

Tank diameter: 48 to 72 inches

Tank length: As long as necessary to obtain given capacity

Pressure/vacuum pump: High-speed, self-lubricating,
air or oil cooled with two-way valve

Auxiliary engine

Hydraulic pump and hoist controls

Pattern width: 12 foot swath at speed of 10 miles per hour

Flotation tire: 15 pounds per square inch ground pressure

Availability.

Ag-Chem Equipment Co., Inc.
4900 Viking Drive
Minneapolis, MN 55935
(612)835-2476

Big A
Rachel Manufacturing Corp.
Box 897
Salina, KS 67401
(913)825-1631

Big Wheels, Inc.
Box 113
Paxton, IL 60957
(217)379-2369

The Calument Co.
340 North Water Street
Algoma, WI 54201
(414)487-5251

Dempster Industries, Inc.
Box 848
Beatrice, NB 68310
(402)223-4026

Industrial and Municipal Eng.
Route 34E
Box N
Galva, IL 61434
(309)932-2036

Finn Krimper

Function.--The Finn Krimper anchors straw or long-fiber mulch by partially incorporating it into the soil.

Description.--The Finn Krimper consists of a series of 20-inch disks spaced 8 inches apart along a horizontal axle. The axle is attached to a heavy frame equipped with steel boxes. The boxes can be filled with rocks for additional weight. The Krimper may be mounted in a three-point hitch or towed. Wheels are available that can be raised and lowered hydraulically for transport. Disk scrapers are standard (Fig. 23).

Techniques.--The disks roll parallel to the direction of travel, cutting narrow grooves in the soil. Some of the mulch fibers are punched into these grooves thereby anchoring the mulch to the soil surface. Penetration should be 2 to 3 inches.

Capabilities.--The Finn Krimper incorporates mulch, such as straw, hay, and leaves, into the soil. Mulch fibers protrude vertically and act as crop stubble to help prevent wind erosion and aid infiltration.

Limitations.--The Finn Krimper should be operated on the contour to prevent water erosion in the grooves. Tractor drawn implements are limited to 3:1 slopes no greater than on which the tractor can operate safely.

Specifications.

Width: 6 or 8 feet

Depth: 1 to 3 inches

Weight: 1,000 to 1,300 pounds

Power requirements (drawbar): 20 to 50 horsepower

Labor and Equipment.--Requires one person to operate the prime mover.

Availability

Finn Equipment Co.
2525 Duck Creek Rod
Cincinnati, OH 45208
(513)-871-2529

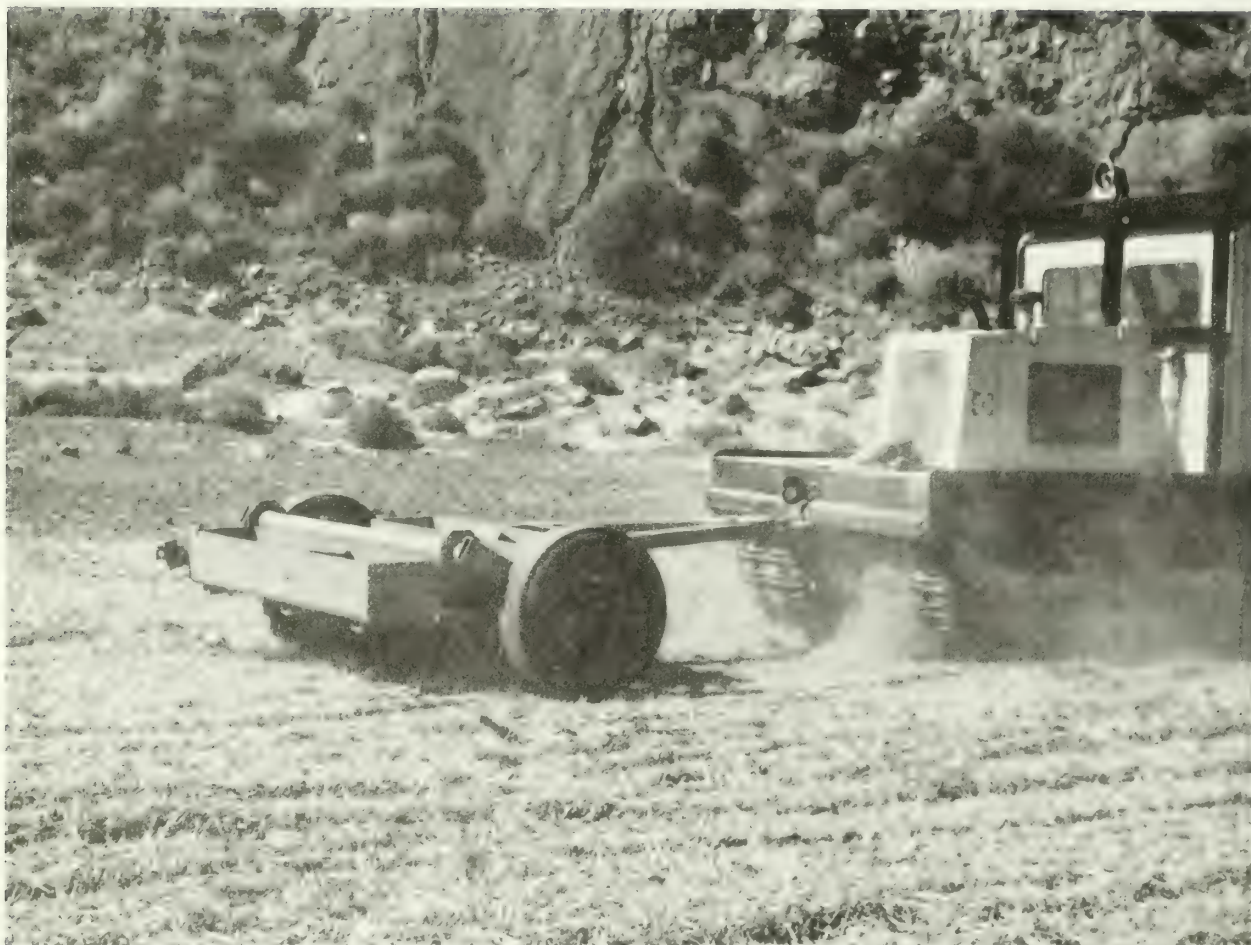


Figure 23.--The Finn Krimper.

Traveling Irrigation Systems

Function.--Self-propelled traveling reel and gun sprinklers are used for irrigating areas with liquid manure or municipal sewage wastewater.

Description.--A self-propelled traveling reel and gun irrigator consists of two pieces of equipment; a gun cart and a hose reel and trailer. The gun or sprinkler is mounted on a tricycle-type carriage with adjustable wheel tread. The hose reel is mounted on a turntable fastened to a high flotation four-wheel trailer. The reel turntable is on ball bearings and will swivel 360 degrees. Hoses are flexible polyethylene. The gun cart is mounted on the reel for transport (Fig. 24).

Techniques.--The reel trailer is towed to the area to be irrigated and connected to the wastewater supply-line hydrant or pump at the mid-point of the first run. The gun cart is lowered to the ground from the reel and hitched to a tractor and towed out unreeling the hose to the distance required (maximum 1,250 feet). The valve is turned on and the tachometer set for the proper ground speed. The gun cart and hose are reeled in at the prescribed speed, stopping automatically when the cart reaches the reel trailer. After irrigating in one direction, the reel is swiveled to irrigate in the opposite direction. The power drive is a radial inflow turbine drive. Engine drive or PTO drive are options.

Capabilities.--Wastewater can be applied to areas 160 to 365 feet wide and up to one-half mile long without relocating the reel. The reel irrigator is especially adaptable to odd-shaped areas. They are easily towed from place to place. They can be set up and operational within minutes. The gun cart does not need to be disconnected for transport. It can be lifted onto the reel trailer with hand-operated jack screw. Flotation tires make units usable on soft ground with little or no compaction of soil. The gun-cart axle is adjustable. The nozzle of the sprinkler will usually clear any solids that pass through the pump screen.

Limitations.--Self-propelled traveling reel and gun irrigators are limited to level to moderate-sloping terrain suitable for agricultural crops. Where wastewater contains solids that may clog the turbine, an engine drive is usually used.

Specifications.

Operating pressure: 60 to 150 pounds per square inch or more at sprinkler head. Minimum pressure at inlet 70 pounds per square inch.

Drive: Radial inflow turbine propulsion, 3-horsepower engine or PTO.

Travel speed: Turbine drive adjustable from 6 to 48 inches per minute. Engine drive 6 to 72 inches per minute. Automatic speed compensator maintains uniform travel speed.

Travel distance: 900 to 1,250 feet each direction (one-half mile total).

Line spacing: 110 to 365 feet wide.

Hose: Polyethylene, 2-1/2 to 4-1/2 inches, inside diameter.

Hose length: 900 to 1,250 feet.



Figure 24.--Water-reel traveling sprinkler irrigation system.
(Photo courtesy of Deverman Advertising)

Capacity: 200 to 600 gallons per minute in depths from 1/4 to 6 inches.

Gun cart: Tricycle-type carriage with rubber tires with adjustable axle from 53 to 144 inches. Crop clearance from 39 to 66 inches high. Nozzle height, 75 inches.

Sprinkler: Nelson P150 to 200R, or equal.

Hose reel: Mounted on two- or four-wheel trailers; core diameter, 96 inches; reel mounted on a swiveling 360 degree turntable.

Towing: 3 miles per hour in field; up to 12 miles per hour on roadway.

Dimensions:

Height: 12 feet 6 inches

Width: 9 feet 8 inches

Length: 20 feet 5 inches

Labor and Equipment.--One person is needed to operate a tractor for transporting the reel and for setting up and towing and placing the gun cart.

Availability.

Ag-Rain, Inc
600 S. Schroder
Havana, IL 62644
(309)543-4425

Long Manufacturing
Box 1139
Tarbo, NC 27886

Center-Pivot Irrigation System

Function.--Center-pivot irrigation systems are used to evenly disperse liquid livestock manures, municipal sewage wastewater, or supplemental irrigation water in land-treatment operations.

Description.--A center-pivot irrigation system has a slurry lagoon or waste pit; an electrical power supply; a turbine pump; and variable sections of 6- to 8-inch, galvanized, flexible, tubular, steel pipeline with uniformly spaced spray nozzles. The pipeline is mounted on an under-truss system supported by triangular steel towers attached to electric drive units with high-flotation or maxi-float rubber tires (Fig. 25).

Techniques.--The slurry material to be sprayed is pumped from the storage lagoon to the center pivot by the turbine pump. The waste is distributed down the entire length of the system as it slowly rotates in a circle around the pivot. A computer is used to calculate the most efficient sprinkler package and the most precise distribution of slurry from one end of the system to the other.



Figure 25.--Center-pivot irrigation system.

Capabilities.--For a quarter section, you can choose an all-terrain, standard span (1,300 feet) system with 7, 8, 9, or 10 drive units with five different span lengths from 105 to 185 feet and capable of climbing 6 to 12-inch ridges and handling stresses on slopes up to 30 percent. There are low- or high-profile units. Low-profile units minimize wind drift and evaporation. High-profile units clear tall crops, dwarf trees, or other objects.

Because a single system travels in a circle or a constant track 8 to 12 inches wide, it eliminates accidental overlapping and over or under application due to variance in spreading volume. It can cover from 10 to 150 acres and is capable of spreading wastes over rolling ground with slopes up to 30 percent. There are tow or no-tow systems. The smaller systems are usually towable and can easily be moved from field to field.

An output of 800 gallons per minute spreads as much as 48,000 gallons of waste per hour. This compares with a 3,000 gallon liquid tank wagon that spreads two loads (6,000 gallons) per hour. Water carries the nutrients down into the soil so tillage is not needed to get waste material into the ground.

Soil compaction is minimal because the wheel track in the circle is always the same, and high-flotation tires minimize rutting.

Limitations.--Only operates in a circle. Works most efficiently above 40°F and when soil is not frozen. Limited to level ground and moderate-sloping terrain (up to 30 percent). Suitable for agricultural crops.

Specifications.

System size:

Length: 1,298 feet

Drive units per quarter section: 10

Rotation time:

Standard (30 rpm): 16.9 hours

Optional (56 rpm): 9.3 hours

Pipe size (12 gage wall):

Outside diameter: 6.625 inches

Pipe height (at drive unit): 12.0 feet

Crop clearance: 9.0 feet

Sprinkler packages:

Standard: 250 gallons per minute

Pressure: 60 pounds per square inch

Spacing equal impact sprinklers: 126 feet

Nozzles: Anticlog

Drive unit:

Tower gear motor: 1 horsepower

Output outer towers: 37 revolutions per minute

Output inner towers: 30 revolutions per minute

Gear case reduction ratio: 52:1

Electrical system:

Motor: 3 phase, 460 volts

Span length: 105 to 185 feet

Maximum slope limitation:

Climbing 0 to 6 inch ridges: 30 percent

Climbing 6 to 12-inch ridges: 30 percent

Tires, high flotation: 14.9 by 24

Labor and Equipment.--One person is needed to operate a tractor for transporting towable systems and for setting up and placing span system.

Availability.

Valmont Industries, Inc.

Valley, NB 68064

(402)359-2201

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Provides information, recommendations, and guidelines for the use of organic materials as mulches in reclamation of coal minesoils in the Eastern United States. Includes a brief description of the environmental impacts of coal surface mining, the problems associated with disposal of organic wastes, and a discussion of mulch in relation to erosion, soil properties, and plant growth. Organic materials that have potential use as mulches for revegetating surface-mined lands are identified and described. Selection criteria for organic materials, application methods, equipment, and requirements are explained.

ODC 232.425.3:114.449.8

Keywords: Mulch, surface-mine, minesoil, reclamation, amendments, straw, hay, chips, leaves, hydromulch, sewage sludge

CONVERSION TABLE - ENGLISH TO METRIC

English unit	Metric unit	Conversion factor
<u>Length</u>		
inch, in	centimeter, cm	2.54
foot, ft	meter, m	0.305
mile, mi	kilometer, km	1.609
<u>Area</u>		
square feet, ft ²	square centimeter, cm ²	929.030
Acre, Acre	hectare, ha	0.405
<u>Weight</u>		
pound, lb	kilogram, kg	0.454
short ton, ton	ton	0.907
short ton, ton	kilogram, kg	907.184
<u>Volume</u>		
gallon, gal	liter, l	3.785
cubic yard, yd ³	cubic meter, m ³	0.764
<u>Yield or Rate</u>		
pounds/acre	kilogram/hectare	1.121
short tons/acre	tons/hectare	2.242
cubic yards/acre	cubic meters/hectare	1.886
gallons/acre	liters/hectare	9.346
<u>Temperature</u>		
Fahrenheit, °F	Celsius, °C	0.555(F-32)

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 - Berea, Kentucky, in cooperation with Berea College.
 - Burlington, Vermont, in cooperation with the University of Vermont.
 - Delaware, Ohio.
 - Durham, New Hampshire, in cooperation with the University of New Hampshire.
 - Hamden, Connecticut, in cooperation with Yale University.
 - Morgantown, West Virginia, in cooperation with West Virginia University, Morgantown.
 - Orono, Maine, in cooperation with the University of Maine, Orono.
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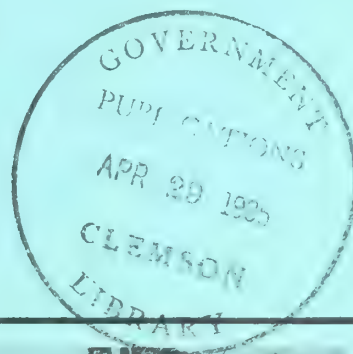
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Region VI Technical Conference



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SPRUCE-FIR MANAGEMENT

AND

SPRUCE BUDWORM

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SPRUCE-FIR MANAGEMENT AND SPRUCE BUDWORM

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INTRODUCTION

Regional Technical Conferences were initiated by the Society of American Foresters in 1982. Since then there have been 8 of them across the U. S., with 8 more scheduled for 1984, including this conference. The basic idea was to foster dissemination of scientific and technological information throughout the profession of forestry, and to do so at the grass-roots level of professional society.

There are 12 Forest Science Regions and they correspond to the 11 Voting Districts of the Society, except for the large Rocky Mountain-Intermountain District which is divided into 2 Regions for better coordination and travel. Conference planning and coordinating in each Region is done by a Regional Technology Committee composed of at least three members from the State Societies within the Region. Each Region is to hold a Technical Conference every second year.

In this area, Science Region 6, the two State Societies, New England and New York, each have a Forest Science Coordinator. Dr. Tom Corcoran (University of Maine) and Dr. Edwin White (SUNY-ESF), along with the Conference Program Chairman, Dr. Daniel Schmitt (USFS-Northeastern Forest Experiment Station) have taken the lead roles in this Conference.

And a fine conference it looks to be. Management of spruce-fir forests in the face of the persistent spruce budworm is a real challenge to resource managers. The topic cries out for a technical up-dating. The last major conference on spruce budworms was in 1984 at Alexandria, Virginia. The Canadian-USA Spruce Budworms Program (CANUSA) has brought concerted research effort to the problem on both sides of the international border that runs through the insect's territory. Managers and researchers need the latest information on the problem.

The first real-life forest insect problem that I encountered as a forester recently out of the University of Montana School of Forestry was western spruce budworm. Of course in those days there was only one spruce budworm--the spruce budworm. (Life becomes more complicated.) My "almost like new" forest entomology notes revealed the scientific name of the beast. I practiced pronouncing it over and over--Choristoneura fumiferana, Choristoneura fumiferana. Then I went into my District Manager's office to tell him what I had found in our stands. He asked if I might know the scientific name of the insect. "Yes I did", and pronounced the name flawlessly. But my composure

was shattered when he said, "You're wrong! It's Tortrix fumiferana." (Another example that things change.)

I have clear recollections of days then when the air in some stands was constantly aglitter with flying moths. And I recall my despair on seeing the effects of the budworm on a young Douglas-fir stand where we had planned a Christmas tree sale for the coming Fall. That was in 1957 and 1958 and spruce budworm was an all too common occurrence for the next few years in southwestern Montana.

The spruce budworm problem has dominated forestry practices in the coniferous forests of eastern North America. It has also become a major social dilemma because of the control practices used against the insect. Traditional cost-benefit analyses fail when applied to the large scales that budworm control projects encompass. The social costs of our projects, particularly the costs related to health effects of spray programs, can be only imperfectly estimated. This failing becomes even more obvious when we look to the long term social costs and benefits of budworm control programs.

Forest management is becoming increasingly complex. Technical forestry principles themselves are more involved not to mention the legal and social environment in which we must manage. Management science has responded to these sorts of complexity with the systems concept. Industrial engineers seem to have been early users of the systems approach, but the idea has spread to many areas, including forestry. Integrated forest pest management is the term often used to indicate use of systems planning approaches for forest insect problems.

The basic elements of integrated forest pest management are that (1) protection planning and implementation are subordinate to forest land management objectives, (2) that the apparent injuriousness of pests must be evaluated within a sound ecological, social, and economic framework, and (3) that complete elimination of naturally occurring pests is not usually a feasible protection goal.

Integrated management of eastern spruce budworm is not yet a reality; the ecological, social, and economic knowledge needed to develop an integrated management system is not available. And it appears to me that this information will not be available for some time. The problem is too vast and complex for quick and easy solution. But I do believe that an integrated systems approach to the problem is the only way that will lead to satisfactory management of the insect. The integrated approach to research and management ensures that the long term view of the problem is adequately considered and evaluated.

In the short term, the options that foresters can use at this time are limited; spray, salvage, and do nothing. None of these options deal very effectively with the underlying causes of budworm

infestations. And the current long term view of spruce budworm "management" is simply a summation of short term actions over time.

The major topics of this conference include most of the major knowledge areas that need to be included in an integrated management system to deal with the insect. Population monitoring capabilities are essential for prediction of outbreaks. Knowing the impact is necessary for assessing costs and benefits of proposed programs. Understanding the roles of predators, parasites, and weather are key factors in judging budworm population strength. Stand hazard ratings and appropriate silviculture provide the forester with longer term options than are now available.

Integrated forest pest management can be described at three levels: a conceptual level, a philosophical level, and a practical level.

A dictionary tells us that a concept is nothing more than an abstract idea; a thought, a notion. The concept, more properly the concepts, of integrated pest management today reflect the changing ideas of how science, technology, and society view pest problems and their solutions.

Philosophies are more concrete than concepts. A philosophy is a theory regarding a sphere of activity or thought. A philosophy has also been called a system of philosophical concepts. Philosophies are based on logical reasoning and analysis of fundamental beliefs. They eventually must be tested by the appropriate segments of society to determine whether they can serve as the basis for practices designed to meet society's needs.

Where are we now in the evolution of forest pest management? The concept of forest pest management has evolved from one of more or less brute force "control" of pests to one that recognizes that pest management activities must be consistent with broader economic and social conditions. And our philosophy, or framework, of pest management, where does it stand now? Scientists and managers have done a good job of weighing scientific and technological knowledge and theorizing its application to pest management and to the broader scope of resource management. Our state-of-the-art pest management philosophies include the ecosystem approach to research and to population regulation; they incorporate benefits and risk consideration, including those relating to non-market effects; and they consider both long-term and short-term intervention as part of a single over-all strategy. Our philosophies appear sound and provide good frameworks for guiding research to practical application of pest management.

Practical applications. Pest management has evolved up to that level, but insects pests are not managed using all of the marbles yet. The practical on-the-ground ways that we deal with pests are changing as a result of our philosophical changes, however. The first changes in the practical level of insect management were in how

we used older existing tactics and practices. The obvious example is insecticides. Schedules have been replaced with timed applications relating to insect densities. The use of some chemicals has been restricted because of environmental considerations and effects on target and non-target organisms.

New tactics and practices also are being included in practical pest management. In the next 3 days we will hear about biorational insecticides, improved detection and monitoring systems, using predators and parasites, and more. Much of this new knowledge is very close to becoming pest management practice.

But the practical level of spruce budworm pest management lags considerably behind where our research philosophy says we could be. This situation should be no surprise to us. Producing new technology, testing it, and adopting it takes time.

There is an intermediate step between our current level of incomplete pest management knowledge and full-fledged pest management system. Resource managers should be able to incorporate new findings into their decision-making system without having to wait for the full and final result. This was the intent of the decision support system for southern pine beetle that I discussed in the compendium on The Southern Pine Beetle (U.S.D.A. Technical Bulletin 1631). Although existing information on the southern pine beetle was not adequate for a full blown pest management system, decision support systems, tailored to fit organizational realities, are feasible and would move southern pine beetle management to a sounder level of practice. Such a system is in reality a sub-system of a more ideal pest management system.

The conference is designed to move us to a higher level of spruce budworm management in the eastern spruce-fir forests. Let's take an upbeat attitude and look for ways that we can use the information that is being transferred to us here.

"BUDWORM! WHAT ABOUT THE FOREST?"

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The importance of the spruce and spruce-fir cover types in eastern North America is outlined.

Biogeographic history of spruce and fir is explained in relation to distribution during the Pleistocene. Evolution of the genus Picea is discussed with respect to continental drift. White spruce is essentially modern, dating from the Pliocene. Red spruce is an older species dating, with Arcto-Tertiary floral associates, from Tertiary times or perhaps earlier. Some genecological concepts are identified. The Genetic distance as related to cross compatibility, particularly in white spruce, is outlined.

The consequences of long selected tolerances not only affected migration and present distribution but also affect management of modern stands. Respective nutrient uptake patterns, productivity and nutrient cycling strategies are demonstrated.

Finally, stand structures and dynamics of white spruce-fir and red spruce-fir forests are related to budworm activity.

Keywords: Spruce-fir; Picea glauca; P. rubens; P. mariana; Abies balsamea; Pleistocene; species assemblages; migration; ecological variation; productivity; nutrient cycling; evolution; paleobotany; genecology; crown form; hybridization; stand dynamics; budworm.

A year or so ago, I attended a Canada-Ontario Joint Forest Research Symposium in Timmins, Ontario entitled "The spruce budworm problem in Ontario - Real or Imaginary." When I came home, I discussed the meeting in general with my wife Jeanne and a number of the papers in particular. She listened with some comment for about half an hour and finally, in exasperation, breaking in, said, "Budworm! What about the forest?" That remark gave me the title of this presentation, an overview of the spruce and spruce-fir forest.

Extent and Importance of the Eastern Spruce-fir Forest

At the outset, I would like to provide an estimate of the enormous extent of the productive spruce and spruce-fir forest of Canada and the United States. Table 1 indicates the total area and volume for eight central and northeastern states. It may be seen that in this area there

Table 1. Area and volume of **Stocked Productive Spruce and spruce-fir forest land***

State	Area 1000 ha	Volume 1000 m ³
MAINE	272	368,167
NEW HAMPSHIRE	25	52,620
VERMONT	16	37,581
CONNECTICUT	7	5,494
NEW YORK	319	54,461
MICHIGAN	83	67,800
WISCONSIN	93	36,080
MINNESOTA	647	45,623
Total	1,462	667,826

*data after USDA Forest Service (1982)

Table 2. Area and volume of stocked productive spruce and spruce-fir forest land*

Province	Area 1000 ha	Volume 1000 m ³
NEWFOUNDLAND	7,297	428,629
NOVA SCOTIA ¹	1,751	124,581
P.E.I.	165	22,036
NEW BRUNSWICK ²	3,197	280,321
QUEBEC ³	33,027	2,792,854
ONTARIO ⁴	15,240	1,473,164
Total	60,677	5,121,585

*data after Bonner (1982)

Supplemental data courtesy:

¹F. Wellings, Forest Resources, Nova Scotia
Dept. of Lands and Forests

²W. Clowater, Forest Development Survey, N.B.
Dept. of Natural Resources

³D. Demerse, Service de l'inventaire Forestier,
Québec Min. de Terres et Forêts

⁴J. Osborn, Forest Resources, Ontario Ministry
of Natural Resources

are 1,462,000 hectares which are equivalent to about 5,624 square miles. The total productive volume stands at 667,826,000 cubic metres. The productive area for six Canadian provinces from Ontario eastward is 60,667,000 hectares or 234,184 square miles (Table 2). The standing volume carried on this area is 5,121,585,000 cubic metres. Since in a number of Canadian provinces black spruce is not separated from white spruce in inventory data, these data also contain extensive areas of black spruce. Some states and provinces, e.g. Minnesota and Nova Scotia, have a great deal of

their spruce and fir associated with hardwoods and the volumes of spruce and fir per hectare appear somewhat lower since hardwood volume is excluded in summation. The sheer extent, its current production and its productive potential provide an idea of the incredible value of these forests. The budworm, with its propensity for periodic epidemic outbreaks, can cause tremendous losses and, as such, is a major component of management consideration of the spruce-fir forest. In addition to the foregoing, the northern spruce-fir boreal forest or taiga also extends northwestwards through northern Manitoba, all the way to Alaska.

To give you some idea of the extent and nature of the harvest in northern Ontario and Quebec, Figure 1 illustrates about a half mile (0.8 km) of stacked full-tree logs. (In full-tree logging, the stump and roots are left on the site. The tops are usually brought out to a primary landing where branches are removed). These log decks are, in effect, a whole spruce forest turned on its side! The height of the near end of the pile is higher than a bus and it may be seen that the small ends of the logs lie away from the road. Another stack is decked up on the other side. There is a second corridor down the far side of these decks and more logs decked beyond. This whole forest will be cut, brought in to this landing and then moved out to a mill. The landing will be filled up again continuously.



Figure 1. Tree length log decks in northern Ontario.

Pleistocene History and the Migration of the Spruce-fir Forest

Figure 2 provides a diagram of North America during full glaciation illustrating the maximum extent of the glacial sheets at about 18,000 years ago. The important thing to note from this is that if one considers the extent of the ice, it may be realized that, apart from a slight possibility in a small unglaciated corner in southeastern Alberta, there was no part of the boreal forest occurring at that time in Canada. The total boreal forest was located south of the glacial front and entirely in what is now the United States. A large refugium-corridor, connected with Beringia (the unglaciated parts of

Alaska, eastern Siberia and the land bridge between them) existed in the central Yukon plain of central Alaska and extended partly into Canada, between the Laurentide and Cordilleran ice sheets. This refugium-corridor was, however, not as convenient as we may wish to presume for the survival of trees and forests.

The area was associated with large ice fronts and the climate was known to be somewhat dry and extremely cold. Flora from pollen diagram and mammalian remains from interior Alaska indicate that the area was essentially a dry steppe-like grassland in some areas, while seemingly a cold steppe tundra in others. While it is known that there were moderate amounts of both white (*Picea glauca*) and black spruce (*P. mariana*), birch (*Betula*) and alder (*Alnus*) in central Alaska during the interstade in mid-Wisconsin times, the climate subsequently became very severe, returning Arctic conditions in late-Wisconsin times. Spruce forests disappeared or were greatly diminished (Matthews 1974). There appears to be no evidence anywhere of any extensive stands from which a great thrust of boreal forest could have re-entered Canada from the northwest. There is also no evidence that any modern spruce species entered North America across Beringia in the Pleistocene or the Pliocene or that any spruce species entered Siberia from North America in this period. There are no white spruce or black spruce anywhere in Siberia or other parts of Asia and there are no *P. obovata*, *P. jezoensis*, *P. koraiensis*, or other Asian species in North American forests. The flora of Beringia in the late Quaternary was essentially that of tundra (Hopkins 1967).

Further inference that the Yukon corridor was utilized by forests migrating northward and not southwards is that there is currently no fir (*Abies*), apart from a few stations of amabilis fir (*A. amabilis*) in southeastern coastal forests in Alaska today, and there is no evidence that there ever was fir in Pleistocene time in continental Alaska. Balsam fir (*A. balsamea*) reaches north-central Alberta from the east, and the range of its close relative, alpine fir (*A. lasiocarpa*), actually makes slight overlapping contact with that of balsam fir in northcentral Alberta. This species extends sparingly into the Yukon from the south, usually at high or moderate elevations, and not reaching the Alaskan border. These firs over their whole ranges grow in association with spruce.

Figure 3 provides an illustration of Pleistocene occurrences of spruce and spruce-fir forests at full glacial and at late glacial periods down to the present Holocene period. Several groups of points may be noted, particularly those on the continental shelf off the coast of New Jersey extending upwards through George's Bank towards Nova Scotia and southwards past Nantucket to Virginia; those in west Texas near the panhandle and northwards along the eastern slope of the Rocky Mountains; and also points in Louisiana and southern Texas. As palynological data continues to be presented, particularly from the northern Great Plains, it becomes evident that there was spruce-fir forest rather continuously all across the whole ice front, extending from the Rocky



Figure 2. North America during full glaciation. Southernmost line represents the maximum extent of ice sheets about 18,000 years ago. Gray area represents ice margin at about 13,000 years ago (Canada 1973).

Mountains and onto parts of the exposed continental shelf of the eastern seaboard. This is not to say that there was a solid, deep spruce-fir forest, only that the type of forest that we have now in the boreal - jack pine (*Pinus banksiana*) and spruce, as well as fir in the east with extensive areas of fire origin poplar (*Populus*), and on some landtypes white birch (*Betula papyrifera*) - extended continuously from west to east in front of the ice. The forest that was present then looks relatively similar to that extant now in the boreal forest from northern Alberta through Ontario to Quebec. This forest was essentially simply displaced southward (Watts 1970; Wells 1970; King 1973). Stand variation, age and composition were related to successional development and site types just as our

modern forest is today.

In addition, fossil mammal remains from the Great Plains to New England and the coast indicate that there were many boreal animals including musk-ox as well as several small mammal species from the modern fauna much farther south (King 1973). Also there were species of woolly mammoth (*Mammotus* sp.) and a wide ranging species of mastodon (*Mammot americanum*). At one time, mastodons were thought to be exclusively browsers, entirely restricted to spruce forests. More recent information suggests they were utilizing both wooded parkland and boreal forest (King 1973). Woolly mammoths were grazers and browsers feeding on tundra grasses, sedges, and conifer foliage such as spruce, fir and pine.

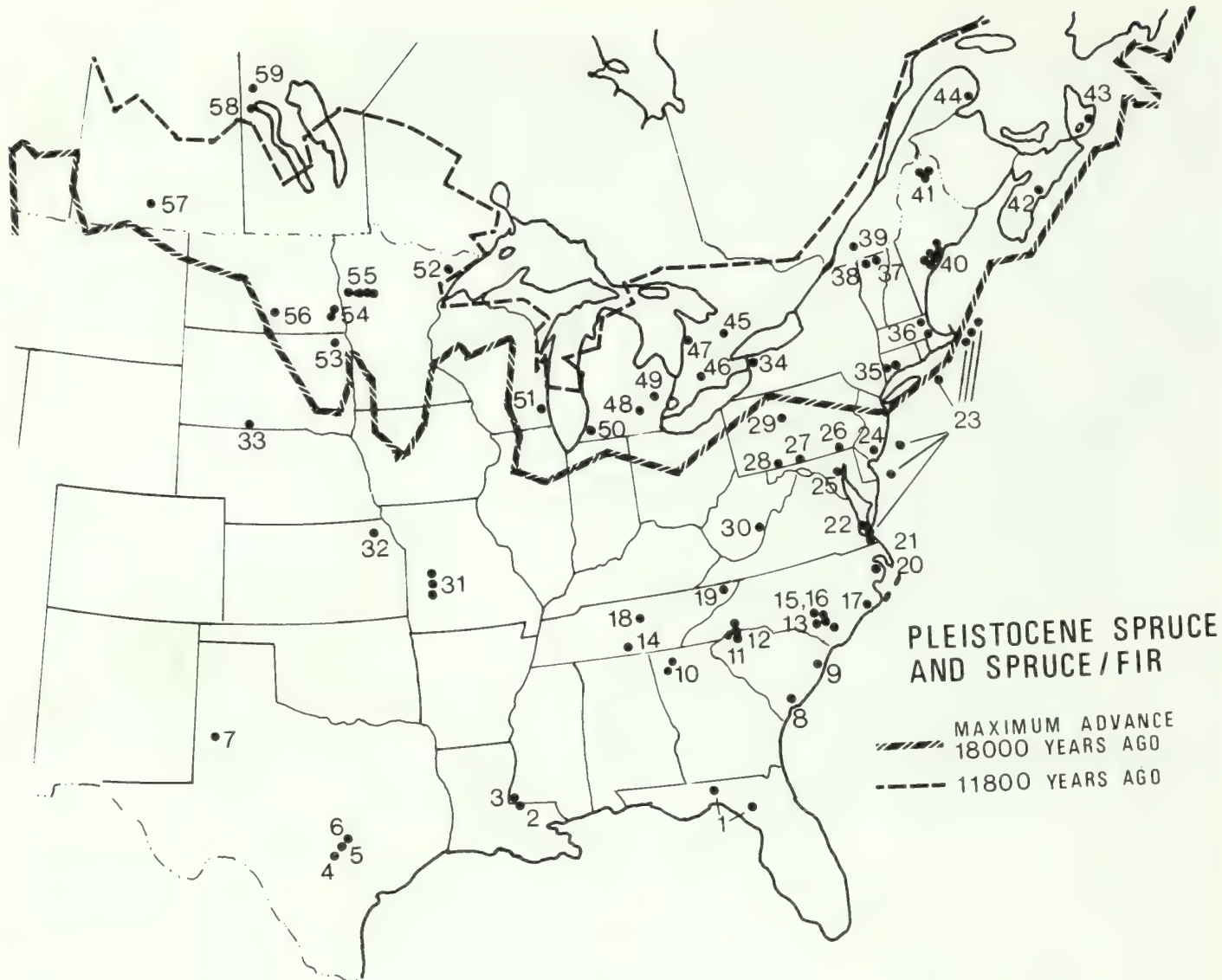


Figure 3. Pleistocene occurrences of spruce and spruce-fir forests at full glacial, late glacial and postglacial periods down to the present Holocene.* Locations: 1. Davis 1946; 2. Brown 1938; 3. Delcourt and Delcourt 1977; 4. Potzger and Tharp 1947; 5. Potzger and Tharp 1954; 6. Graham and Heimsch 1960; 7. Hafston 1961; 8. Leopold 1959; 9. Frey 1952, 1955; 10. Watts 1970; 11. Whitehead and Barghoorn 1962; 12. Cain 1944; 13. Whitehead 1967; 14. Delcourt 1979; 15. Barclay 1957; 16. Frey 1951, 1953; 17. Davis 1963; 18. Delcourt 1979; 19. Buell 1945; 20. Whitehead 1963; 21. Whitehead 1965; 22. Terasmae (in: Harrison *et al.* 1965); 23. Emery *et al.* 1967; 24. Potzger 1945; 25. Knox 1962; 26. Martin 1958; 27. Martin (in: Guilday *et al.* 1964); 28. Schrock 1945; 29. Sears 1935; 30. Darlington 1943; 31. King 1973; 32. Horr 1955; 33. Watts and Wright 1966; 34. Miller 1973; 35. Leopold 1956; 36. Davis 1958; 37. Miller and Thompson 1979; 38. Davis 1965; 39. Terasmae and Lasalle 1968; 40. Potzger and Friesner 1948; 41. Deevey 1951; 42. Livingstone 1968; 43. Livingstone and Estes 1967; 44. Livingstone 1968; 45. Terasmae and Matthews 1980; 46. Mott and Farley-Gill 1978; 47. Anderson 1979; 48. Andersen 1954; 49. Stoutamire and Benninghoff 1964; 50. Potzger 1954; 51. Wilson 1936; 52. Cushing 1967; 53. Watts and Bright 1968; 54. McAndrews 1969; 55. McAndrews 1967; 56. Moir 1958; 57. Ritchie and DeVries 1954; 58. Nichols 1969; 59. Nichols 1969. *Map modified after Stalker (1977).

Their remains have been found in Missouri, Michigan, New England and other places (Stoutamire and Benninghoff 1964; Whitmore *et al.* 1967).

There were other forest discontinuities along the ice front, occasioned by cold local climates and topography. In New England, for example, there was extensive tundra (Davis 1969). In the southern United States modern interpretation indicates that

many southern hardwoods had compressed ranges, and here and there, in different kinds of niches, there was good survival of many Appalachian species (Watts 1970; Delcourt and Delcourt 1977). In the southern Appalachians migration is a little more complex. Early records indicate that the most logical interpretation is that both black and white spruce and jack pine extended southward on both sides of the Appalachian Mountains (Watts 1970).

There were two peaks of spruce, however, and one possible explanation is that the second peak in spruce in the late glacial (Leopold 1956; cf. Terasmae and Lasalle 1968) may have been the expansion of red spruce (*Picea rubens*) in some areas (Gordon/Leopold 1970, pers. comm.) closely followed by hemlock (*Tsuga canadensis*) (Pötzger and Friesner 1948; Davis 1969). Many of these red spruce sites are not far from current areas of red spruce at higher elevations and in the Maritimes.

While pioneering chronological studies lacked good comparisons with sites of modern pollen rain, studies in more recent times have included comparative modern pollen rain data (Webb 1974) from similar but more northern sites. Correlations have been made, for example, between palynological sites in New England and northern Quebec (Davis 1969); Missouri with Great Lakes and eastern Canadian sites (King 1973); as well as comparisons with standing basal area (Leopold 1964).

As might be expected, there have been some interesting and fairly universal misinterpretations. A number of palynologists have shown that some sites located on the Great Plains indicated the presence of ash (*Fraxinus*) along with spruce in the pollen record and stated that no such stands were extant today (Baker 1965; Lichti-Federovich and Ritchie 1965; Cushing 1967; McAndrews 1967; Davis 1969; Gordon/Leopold 1970, pers. comm.). The interpretation of this and other observations (e.g. *Artemisia* and *Picea*) and even paleontological assemblages such as walnut and spruce led palynologists and paleobotanists to think that such species assemblages had no modern analogues, or that in a paleontological sense, some species had changed their ecological characteristics. In fact, there is no evidence that they have. These species have certain kinds of morphologies which are predicated on selection for certain ecological environments. They are unlikely to keep morphological characteristics constant through great ages of time if they have also been constantly changing their physiological tolerances. The unfamiliarity with species' site tolerances and requirements and with the present boreal forest itself, has also been misleading. In fact, there are a number of places in the north where white spruce does grow in proximity to black ash (*Fraxinus nigra*)! Figure 4 illustrates such a stand in the boreal forest of northern Ontario. The ash are growing in a site we call an ash flush about 120 m (6 chains) wide and about 0.8 km (0.5 miles) long. It is base rich - flushed with bases at higher concentrations than those of the surrounding physiographic sites. White spruce, balsam poplar (*Populus balsamifera*) and trembling aspen (*P. tremuloides*) occupy these adjacent sites. In this figure, a small lake is located in the immediate background. Any pollen rain studies from that lake would give substantial mixes of ash and spruce pollen together in the same diagram. It is a widespread but not a common phenomenon in the boreal forest, and is predicated on species requirements and edaphic limitations.

The soils of the Great Lakes, with their relatively high base status and consequently high pH, are not at all like the acidic granitic tills of the Canadian Shield. But, find occasional

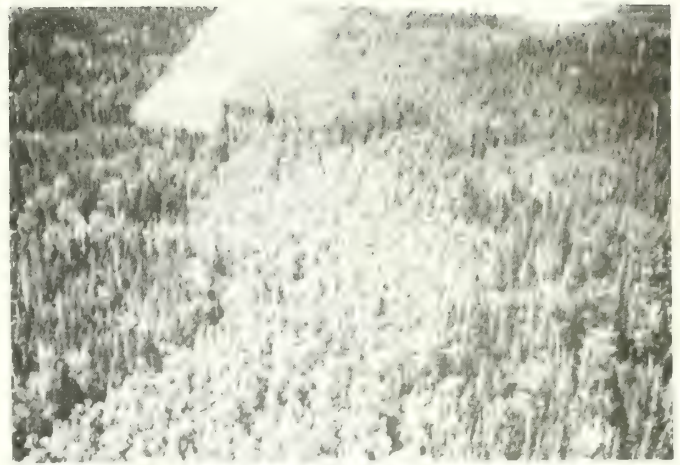


Figure 4. An ash flush in the boreal forest, northern Ontario. The associated stands contain white spruce, balsam fir, trembling aspen, balsam poplar and some black ash.

pockets of like soils in the shield, and there is the species assemblage. Most of the sites from which chronological data is currently being collected have modern counterparts in stand composition and successional stage at a number of places in the current boreal forest or taiga.

The question arises as to how, for example, do we know, from the pollen record, a spruce was red, white or black in the mid-Appalachians. Early studies (Frey 1951) utilized some small differences in pollen size. There was size overlap, however, particularly in the pines, and some palynologists questioned the ability to separate such species as red pine (*Pinus resinosa*) from jack pine (Whitehead 1964) as well as to differentiate among the spruces with complete certainty. However, more recent studies (Birks and Peglar 1980) have identified other pollen characteristics, undulating cap margins, irregular reticulation in the sacchi, etc. as well as the use of discriminant function analysis, all of which have enabled confirmation of earlier findings regarding *Picea*.

Arguments regarding, for example, the inability to separate pollen of red pine and jack pine due to size overlap did not take sufficiently into account those species' edaphic and climatic requirements and tolerances, their associated species and the presence of nearby macrofossils (cf. Whitehead and Barghoorn 1962; King 1973). When a pine species, red or jack, occurs with black spruce and such non-arboreal northern species as *Myriophyllum farwellii*, *Lobelia dortmanna*, *Sanguisorba canadensis* (Whitehead and Barghoorn 1962; Watts 1970) as well as *Arceuthobium pusillum*, the pine will be confirmed as jack pine rather than the temperate red pine.

A further point of interest has been the consistent presence of dwarf mistletoe (*Arceuthobium pusillum*) in the pollen record of the southern Appalachians (Whitehead and Barghoorn 1962) and as far south as Georgia (Watts 1970). Dwarf mistletoe, in host preference, is almost entirely restricted to black spruce. It does occur very rarely on red

spruce, although not presently in the southern Appalachians, and rarely on white spruce. During full and late glaciation, its consistent presence, along with black and white spruce and jack pine, suggests its association is most logically attributed to the boreal spruces.

The confusion among some palynologists with respect to the nature of the boreal forest may have been compounded by a number of phytosociological studies referring to north temperate montane and southern Maritime forests as 'boreal' when they were not. The floristics have similarities but differ in other respects. Still, in some recent literature, they remain described as 'boreal'!

At full glaciation, the boreal forest, dominated by jack pine growing on freely draining sandy plains, and accompanied by the boreal white and black spruces, reached northwestern Georgia (Watts 1970). In the late glacial in Louisiana (Delcourt and Delcourt 1977), southern Texas (Potzger and Tharp 1943, 1954) and probably northern Florida (Davis 1946) the boreal forest outliers were in fact just that. They were not part of a big continuous band of boreal forest extending down that far south, but rather outliers of the boreal such as one finds in parts of New Hampshire today.

Ecological Variation in the Spruce-fir Forest

For the purposes of this overview, a catalogue of phytosociological studies is avoided. Rather, examples of the principal types of spruce and spruce-fir forests are illustrated which demonstrate the wide ecological amplitude embraced by this forest.

The boreal forest or taiga is characterized by few arboreal species. In North America, the principal species are jack pine, which grows on pure stands or associated with black spruce and occasionally trembling aspen, white spruce which grows in cyclic association with trembling aspen or balsam poplar, and in the east, balsam fir. Eastern tamarack (Larix laricina) is widespread. Minor species include several species of alder (Alnus sp.), mountain ash (Sorbus sp.) and willow (Salix sp.). In the north this forest includes the spruce-muskeg as well as the spruce-lichen parklands and spruce ericaceous tundra ecotones; along the southwestern edge, the spruce-aspen-grass parklands; and in the east, enclaves of north temperate forest species.

What is the great spruce and spruce-fir forest like? In northwestern Ontario, white and black spruce are often associated together, along with balsam fir and aspen. This association also occurs in the Green River area of northern New Brunswick, but over much of their range, edaphic controls separate these species out more distinctly, balsam fir being frequently found growing in mixtures with white spruce or red spruce, but not black spruce.

Pollen records from Texas also indicate that, in the Pleistocene, fir grew more with white spruce

than with black (Potzger and Tharp 1954). A point of interpretation about the pollen record is that the pollen of balsam fir is heavier than that of spruce, and while it does occur here and there in the pollen record, fir is usually under-represented (Davis and Goodlet 1960). Studies have been done to indicate that spruce pollen in the modern pollen rain is very closely representative of actual basal areas in the surrounding stands (Leopold 1964). Pines are usually much over-represented.

Figure 5 illustrates a subarctic spruce-lichen forest which occurs in the far north of Quebec, Ontario, Labrador and the Northwest Territories. Other associates which occurred earlier in post-glacial time have dropped out. There are great rock and outwash sand plains supporting lichen in a park-like forest which, depending on exposure and moisture regime, is intact in all the depressions. Such areas are much utilized by caribou for both food and shelter.

Figure 6 also illustrates a subarctic spruce forest. This is an upland forest with widely distributed black spruce with an ericaceous heath growing vigorously between all the trees. This forest is widely distributed from northern interior Alaska, across the Northwest Territories to Newfoundland.

A bit farther south - in parts of Alaska, the eastern Northwest Territories, northern Manitoba and Ontario on the Hudson Bay lowlands (Fig. 7) - the first closed boreal forest occurs, consisting of white spruce and aspen on the slightly higher eskers and postglacial beaches, while immense flats of small black spruce are found in the poorly drained intervening areas. These areas are often also associated with long string bogs, frequently without spruce, but rather, with eastern larch.

In interior Alaska (Fig. 8), successional stages of black spruce and ericaceous heath may be found at moderate elevations and following fire (Fig. 8, foreground). These stages are followed on north slopes by continuous and closed stands of black spruce (Fig. 8, background) (Viereck et al. 1983).

Figure 9 shows the south slope of the same area which is occupied by tall aspen, pure stands of white spruce, and mixed white spruce and aspen. The climatic delineation of these two spruces is dramatic in interior Alaska, the north slopes being almost entirely black spruce, and the south slopes largely white spruce (Viereck et al. 1983).

Stands of white spruce of magnificent form - tall linear-crowned trees - are very common in interior Alaska (Figs. 10, 11) (Juday and Zasada in press). The ground vegetation is feathermoss (Hylocomium splendens, Pleurozium schreberi, etc.). Such stands are also common in northcentral Quebec although they are generally considerably younger and are spruce-fir rather than pure spruce.

Figure 12 demonstrates gradual deterioration in interior Alaska. The tall white spruce decline. The stand gradually breaks up with no regeneration



Figure 5. Subarctic spruce-lichen forest (lichen tundra-forest ecotone) in northern Quebec.



Figure 6. Subarctic spruce-ericaceous forest (ericaceous heath tundra-forest ecotone) in northern interior Alaska.



Figure 7. Closed high boreal forest, Hudson Bay lowlands, Ontario. White spruce, aspen and white birch on eskers and beaches, black spruce on poorly drained flats, larch in the string bogs.



Figure 8. North slope black spruce, interior Alaska.



Figure 9. South slope white spruce and aspen, interior Alaska.

and black spruce commence to invade. This kind of stand transformation comes about through nutrient depletion on fresh or moderately drained floodplain sites or paludification on moist or wet sites. These are active processes in Newfoundland and Labrador, northern Quebec and Ontario through to Alaska. The black spruce succeeding on such sites usually become dominant for a rotation or so but are of low quality.

Figure 13 shows a black spruce ecosystem site in interior Alaska with an average age of 120 to 140 years (Viereck *et al.* 1983). Such stands are sometimes referred to as the 'drunken forest'. The trees are about eight metres high and of very small diameter. They are all leaning in various directions. Similar stands occur at the higher latitudes in northwestern Ontario.

The Green River area in northern New Brunswick is a typical closed boreal forest. Figure 14 demonstrates the massive catastrophic deterioration of white birch and the cyclic replacement by the spruce-fir forest coming up through it. This forest is now



Figure 10. Tall linear-crowned white spruce in interior Alaska.



Figure 12. Interior Alaska degraded white spruce site; black spruce beginning to invade.



Figure 11. Interior Alaskan long-boled white spruce; feathermoss floodplain site. Stand age up to 240 years.



Figure 13. The 'drunken forest'. Mature black spruce growing over permafrost. Interior Alaska.

much more dominated by fir than in former times as a result of cutting and budworm spraying practices.

Where the boreal spruce-fir forest impinges on the north temperate forest the composition of the stands is frequently under edaphic as well as climatic control. Successional stages are also of influence as are the number of species involved and individual species tolerances.

Figure 15 shows such an area in the Algoma region of Ontario. Examples such as this are repeated endlessly across southcentral Ontario,



Figure 14. Green River, northern New Brunswick 1962. Catastrophic dieback of white birch. Rising regeneration predominantly fir with some spruce and white birch.



Figure 16. Red spruce-fir stand in a 'sea' of tolerant hardwoods, southcentral Ontario.

Quebec, northern Vermont and New Hampshire. This is a north temperate forest showing very tall white spruce and good balsam fir, surrounded by other sites which are supporting tolerant hardwoods. There is a ridge in the background with hemlock and white pine (*Pinus strobus*). This kind of stand is common throughout northern New England. It could well have been the kind of stand that provided the pollen rain for the Louisiana sites during late glaciation, not large, but repeated over and over again with nearby associated hardwood areas.

Figure 16 shows a pure intact stand of red spruce and balsam fir in southcentral Ontario. It is encompassed by a 'sea' of tolerant hardwoods with a few conifers. This is very similar to southern



Figure 15. Algoma, central Ontario. North temperate boreal forest with white spruce and fir.



Figure 17. Northcentral Ontario, north temperate forest; hardwood niches in a 'sea' of boreal spruce and fir.

Appalachian stands today. When cooling glacial climates put pressure on temperate hardwoods, the areas they occupied would diminish and conifers would advance out across these hardwood areas. The hardwoods would persist in their own special niches, and to some extent in mixtures, but the general niche of the conifers would expand.

By moving northward two and one half degrees in latitude to the northern part of Algoma in northcentral Ontario (Fig. 17), an idea of what that shift would have been like is provided. Here, it may be noted, is a great sub-boreal forest filling all the valleys and sweeping across the landscape. The 'sea' is now composed of mixed conifer stands. The tolerant hardwoods are confined to their niches here and there, and may be noted as light patches on the southwest-facing ecoclimatic sites on the upper slopes. The rest of the country is all boreal spruce and fir.

Moving westward, Figure 18 provides an example



Figure 18. Cypress Hills, southeastern Alberta sub-boreal forest: white spruce and lodgepole pine.

of what some of the boreal forest may have looked like on the Great Plains in the west. This is in the Cypress Hills in southeastern Alberta and southwestern Saskatchewan. These are pure white spruce and lodgepole pine (*Pinus contorta*) stands. This relatively small block of land is of moderate elevation above the general plain. It demonstrates that the local climate can hold sub-boreal forest here. On the nearby plain on a lower slope, there is another fragment of the same stand as well as examples of spruce-aspen parkland. These are modern stands, but during late glaciation, or presently, given any cooling climatic shift, this stand could expand from here and advance across the visible plains to join up with other stands at great distances. There are no other spruce in this particular instance within 280 km (175 miles), but this is clearly a glacial remnant. Pollen and macrofossil data indicate that such forests were widespread on the northern Great Plains (Wells 1970).



Figure 19. North temperate forest; white spruce-black ash flush, central Ontario.

Referring back to commentary on some of the palynological studies indicating that ash and spruce were not associates, Figure 19 provides an example in the north temperate forest of Ontario where black ash and white spruce are growing well together. Both species are tall, emergent trees. They are in a valley here surrounded by other forest types but the stand will repeat itself in this edaphically restricting site. The regeneration consists both of ash and spruce.

Information is accumulating on the nature of the postglacial migration of white spruce in eastern North America. The first of these is phytosociological data (Löve 1959) which showed that there is a separation of an eastern and western component of floristic associates of white spruce. One group, called the 'eastern boreal element', migrated in a northerly direction from the Great Lakes area into eastern Manitoba and around the north ends of the prairie lakes. A second group of plants, the 'western boreal element', invaded Manitoba from the west. Some members of this western group migrated as far east as James Bay. White spruce were associated with both of these migrations.

Holst (1960) from preliminary provenance studies was the first to suggest the possibility of two clines of white spruce from south to north, one east of the Ottawa valley and one west. Nienstaedt (1968) showed from available provenance material that the southeastern distribution of white spruce was in all likelihood a two-pronged cline extending into northwestern Canada on the west side of Hudson Bay and into Labrador on the east. These findings were further elucidated by Wilkinson *et al.* (1971) who showed, utilizing cortical oleoresin monoterpene composition of white spruce provenances, that there were indeed northeast and northwest aggregations in white spruce populations. The principal division occurred up the Manitoba-Ontario boundary to the northwest and eastwards to Labrador, similar to the inferences of Löve (1959). There was also a minor division from the southeast up the Ottawa valley.

The immensity of the range of white spruce provides the principal clue to the great ecological diversity and the related genetic selection embraced by this species. A number of ecologically distinct sites and associations, for example, shallow calcareous soils, and even northern alkaline swamps have not been mentioned in this overview.

The place of fir in the forest is also of prime importance. Balsam fir is a boreal species by origin - its prime centres in the east are in the Maritimes and parts of Quebec. Inventory data in Ontario suggests that relative to other species, it represents only a small percentage of softwood volume. It becomes a somewhat weaker competitor as it goes to the northwest in northern Manitoba and Saskatchewan. Its range sparingly overlaps that of its Rocky Mountain variant, alpine fir, in central Alberta (cf. Parker *et al.* 1981). The latter species, while fairly widely distributed in uplands of the Yukon, does not get into the main part of Alaska, although at high elevation it is present along with spruce and mountain hemlock

(*Tsuga mertensiana*) in coastal southeastern Alaska. *Amabilis fir* is mentioned previously.

Balsam fir in the northeastern forests is not nearly as long-lived as spruce and rots out much earlier. However, regardless of its volume as it approaches maturity, its regeneration is extremely aggressive, both in Ontario and eastwards, and much more so than that of spruce. There are always new and rising waves of fir regeneration in much of the northeastern spruce-fir forest. In parts of central and northern Maine and northcentral New Brunswick, it is near the centre of its biotic potential. The best stands of almost pure fir which occur in Quebec and northern New Brunswick might give the impression that this is predominantly what that country has produced. However, historical accounts of much of this area indicate that enormous volumes of spruce have been cut out there in the past, e.g. in the Miramichi area (Long B.D. 51, 1962, pers. comm.). The forests have experienced a marked shift as a consequence of man's activity and in the face of the much more successful regeneration capabilities of balsam fir.

In the Adirondacks (Adams *et al.* 1920) and in the northern Appalachians, pure balsam fir on the upper slopes of the higher peaks represents a true boreal forest above the temperate montane red spruce, and red spruce-balsam fir mixtures on the midslopes. These balsam fir forests replace themselves through a process described as fir waves. All the trees in an elevational band reach natural rotation age and die about the same time. Regeneration commences in the openings and the whole wave gradually advances upslope in the direction of the wind flow (Sprugel 1976; Sprugel and Bormann 1981). Above the fir forest there may also be scrubby balsam fir and, higher up, black spruce krummholz such as one finds on Mount Katahdin, Mount Marcy and Mount Washington (Löve and Löve 1966).

In the southern Appalachians, balsam fir intergrades with fraser fir (*Abies fraseri*) (Robinson and Thor 1969), an endemic species of high elevation in the south. Red spruce and fraser fir both have temperate montane characteristics: for example, flushing much later than does balsam fir.

The Productivity, Structure and Functioning of the Spruce-fir Forest

Differences in productivity related to shifts in latitude and to differences in site and forest type are presented in Table 3 (Gordon 1983). In the eastern boreal forest, a very common condition of white spruce stands is that they are usually mixed with balsam fir and white birch, or with aspen. Stands may be pure conifer or mixedwood. The two white spruce mixedwood stands, which are still carrying the shorter-lived species, are on different sites accounting for dry matter productivity differences between 4,742 and 5,755 kg ha⁻¹year⁻¹. While these mixedwood sites are quite different from the black spruce sites, the productivities are equivalent. The latter are both Site Class 1 black spruce stands (Plonski 1956).

Table 3. Aboveground productivity (litterfall plus increment) in kg ha⁻¹year⁻¹ for five spruce and spruce mixedwood stands.

Lat.	Site	
45°30'N	Red spruce mature - fresh till	8703.7
46°42'N	Black spruce immature - fresh outwash sand	5742.3
49°15'N	Black spruce mature - moist peat	4568.3
49°12'N	White spruce Mixedwood mature - fresh-moist silt, fine sand	5755.0
49°33'N	White spruce Mixedwood mature - fresh till	4742.4

Black spruce also grows, however, on wetter sites than these highly productive sites, and as moisture regime increases (gets wetter), productivity of black spruce decreases. Red spruce stands on the fresh till are much farther south in the north temperate forest and have a higher productivity reflecting better climate. These are measures of very productive forests of spruce and spruce-fir types on sites on their respective moisture catenas. At lower site classes at these same latitudes there would be much lower productivity.

Figures 20 and 21 (Gordon 1983) present examples of nutrient cycles in a north temperate red spruce stand and in a boreal white spruce mixedwood stand. The structure and functioning of these stands are somewhat similar so the cycles are expected to be more similar to one another than they would be to that of other species such as pure hardwood stands or other conifers. There are some differences, however, which are a consequence of the differences in the nutrient status of the sites on which these types grow. Red spruce stands are normally found on more acidic sites than those on which white spruce mixedwood would grow. This red spruce stand is predictably more acidic: compare calcium levels in the reserves - for red spruce 399 kg ha⁻¹ vs. 1918 kg ha⁻¹ for white spruce mixedwood. More rapid turnover rates are expected in the white spruce mixedwood and more accumulation in the red spruce stand. For nitrogen in the red spruce stand, there is more than one and a half times as much nitrogen in the reserve components as there is in the white spruce mixedwood. However, the amount of nitrogen being cycled as exemplified by uptake is approximately the same.

Both phosphorus and magnesium have substantially greater amounts in the reserve components of the white spruce mixedwood than in the red spruce and this is reflected in the lower amounts involved in uptake in the red spruce stand. These amounts are, nevertheless, sufficient for adequate growth in a less demanding species like red spruce. In the case of calcium, the white spruce has five times more in the reserves than that of the red spruce and yet strangely, the amount of calcium cycling in the red spruce is nearly equivalent to that of the white spruce mixedwood.

Red Spruce (fresh till)

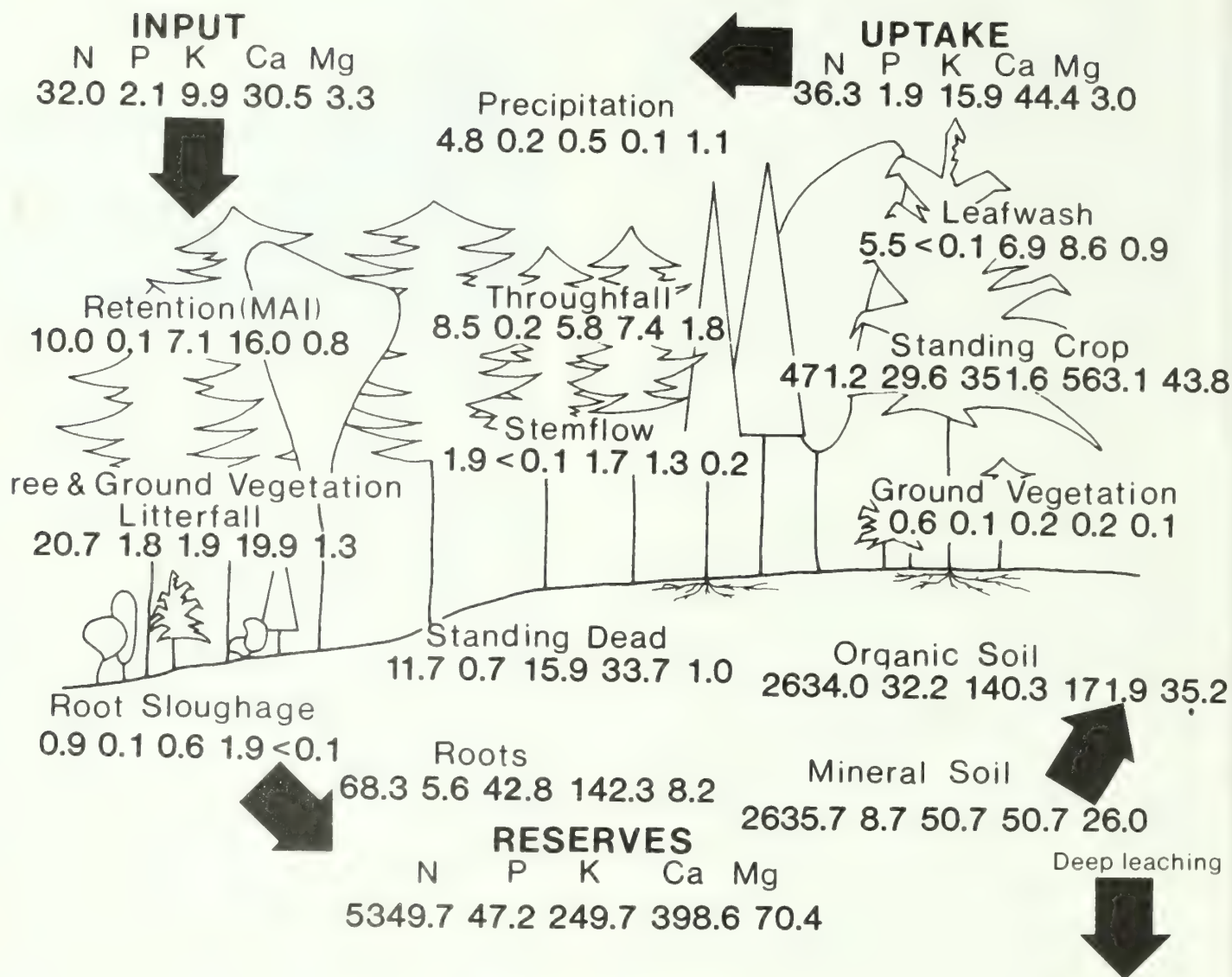


Figure 20. Stylized nutrient cycle (kg ha^{-1}) of a north temperate red spruce forest on fresh granitic till. Species represented are red spruce, balsam fir, eastern hemlock, yellow birch and sugar maple.

For potassium, the amounts in the reserve components are about the same in both stands but the red spruce are getting by with about two-thirds of that of the more demanding species in the white spruce mixedwood stand. Incidentally, balsam fir are present in both of these stands.

Evolution of the Genus *Picea*

The evolution of the genus *Picea* and more particularly the origin of white spruce is important since it is the principal and constant constituent of the boreal spruce-fir forest of North America. As recently as 1955, and even later, Beringia, which was exposed off and on from the mid-Pleistocene at least to mid-Wisconsin time, was considered to be the likely route through which spruce entered North America and

diversified. At the same time, it was well known to many paleobotanists that there were fossils dating back to much earlier times through the Tertiary in a number of places in North America. As the reality of continental drift (Melville 1966; Wilson 1966) began to become more widely accepted in the late '60s, it became evident that the advent of *Picea* into North America had indeed taken place much earlier in the Tertiary or even the Cretaceous (65 million years ago) before continental drift had isolated North America (Gordon 1968).

It is generally accepted that conifers originated before the angiosperms (Florin 1963; Sneath and McKenzie 1973) and that the latter were indeed very common in the Cretaceous period. Spruce-like fossils are very rare, however, in that period although pine fossils are fairly common. There are at least two reasons that there are few examples

White Spruce Mixedwood (silt, fine sand)

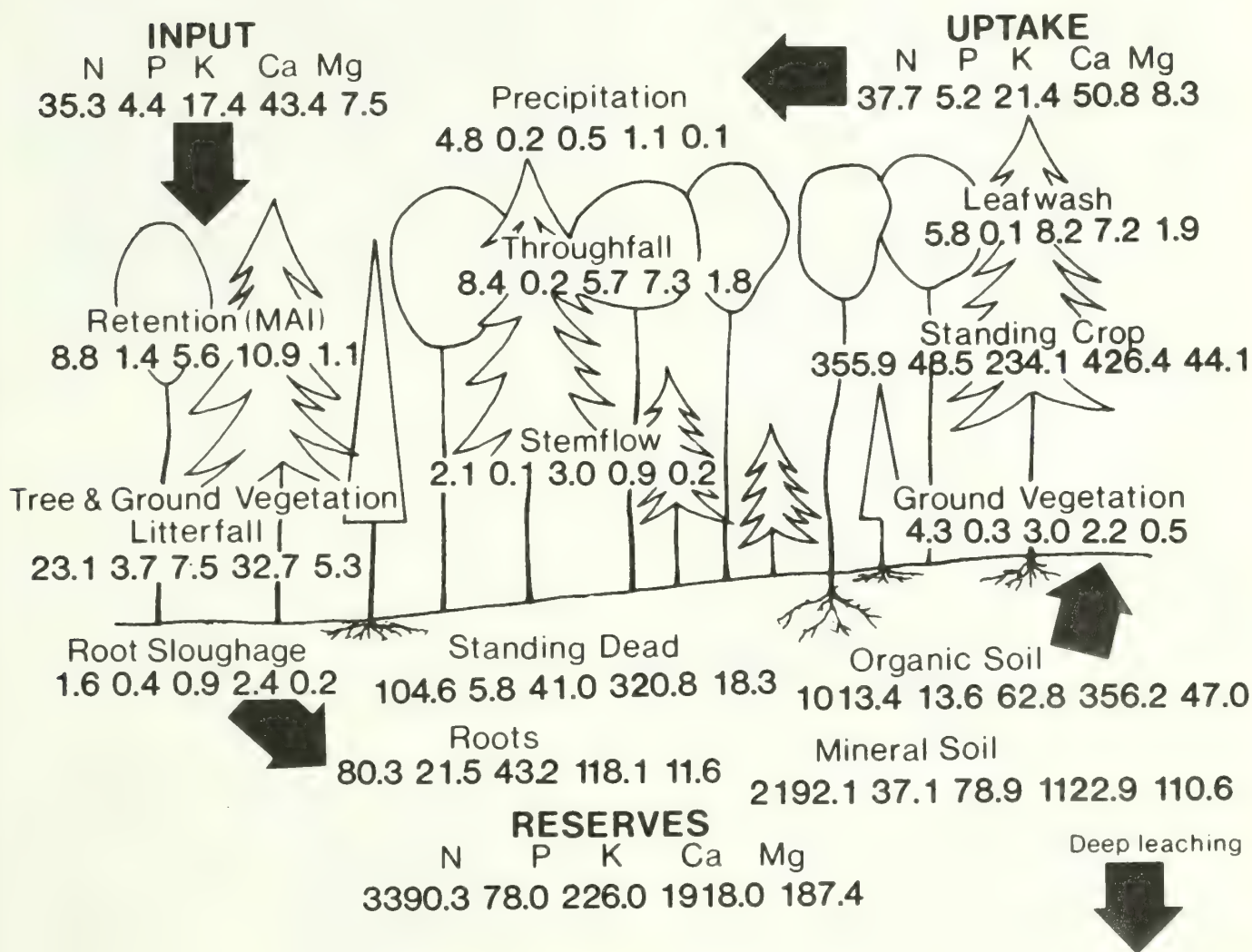


Figure 21. Stylized nutrient cycle (kg ha^{-1}) of a boreal upland mixedwood on silt, fine sand. Species represented are white spruce, balsam fir, trembling aspen and white birch.

of *Picea* from the Cretaceous. Their origin and radiation from the *Pinaceae* may not yet have occurred (Miller 1976), and just as likely, the sites on which *Picea* grew were mostly upland and not near good sites of preservation.

Miller (1976) very thoroughly evaluates early fossil *Pinaceae* from the Cretaceous and onwards. Floral or fruiting parts of plants are the most constant attribute through time in fossil evaluation. An extremely small number of traits (one or two) involving the number and configuration of resin canals in cone scales of conifers, so far has proven to be of high diagnostic value in relating fossil specimens to different species and genera. The small number of Cretaceous spruce-like fossils thus far found in North America has been disqualified as *Picea*, and assigned to other extinct genera, although fossil *Picea* specimens have been obtained from the late Cretaceous in Europe. It is generally accepted that late

Cretaceous thus far represents the age of the genus.

The flora of the northern hemisphere has been essentially modern since the Pliocene (about 11 to 2 million years before the present) and have come down to us from that period through the Pleistocene to the present with very little change. More precise information as to when species arose, separated or diversified would aid in our understanding of taxonomic relationships and chemical and genetic bridges and barriers that are being encountered in breeding work. Many of the species involved are from different continents which have been separated for very long periods of time. This understanding, in turn, helps greatly in developing tree improvement strategies.

In the case of North American native spruces, white and black spruce are both modern species. There are no fossils older than the Pleistocene and Pliocene. Red spruce on the other hand appears

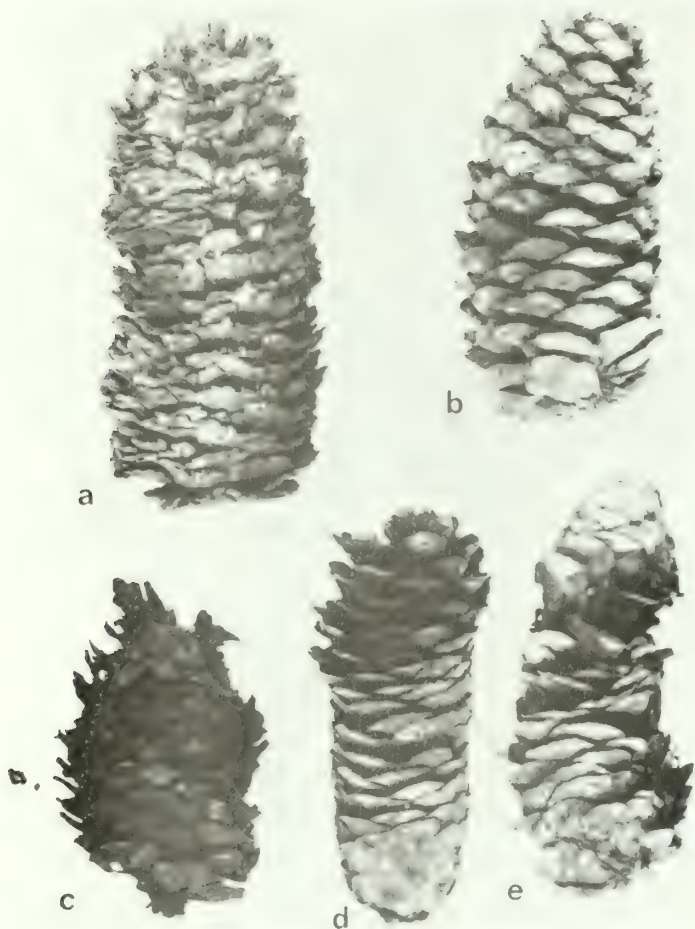


Figure 22. Fossil *Picea banksii* cones from the late Miocene. Banks Island, northwest Canadian arctic (Hills and Ogilvie 1970).

to be an older species. It grows with flora known as the Arcto-Tertiary flora and has been associated with that flora for a very long time, well back into the Tertiary period. It has affinities with a number of older Eurasian species (Gordon 1976). Many other hardwood species in the southern and central Appalachians have occupied and have been migrating up and down the Appalachians throughout the Tertiary period and since.

Genecologists, in common to some extent with paleobotanists, look upon new and old species as having different attributes. One of these is that in general old species, e.g. *Qinkgo*, *Liriodendron*, tend to have no, or fewer, enemies than new species or they have come to terms with those that they have (Wright 1955). Young species tend to have a wider array of pests or enemies and these often occur in epidemic proportions. Also, old species tend to have shrinking ranges.

Apart from common *Juniper*, and its co-Pleistocene companion species, black spruce, white spruce has a range far greater than any other North American conifer. None other of the *Pinaceae* have ranges which are anywhere near as large. Its range is much greater than its associate balsam fir. Its present range is with few exceptions restricted to landscapes which have been glaciated. No fossil counterparts extending back beyond the Pliocene

have been located as yet. Its closely-related montane counterpart is Engelmann spruce (*P. engelmannii*) with which it freely hybridizes. This species however has a fossil counterpart, *P. lahontense*, which is known from a number of sites in Idaho, Oregon and Colorado, back through the Miocene and Oligocene epochs from approximately seven to thirty-eight million years before the present.

One other interesting possibility is *P. banksii* (Hills and Ogilvie 1970), a fossil species from the late Miocene (Fig. 22). Some of the cones of this species, however, are quite different from those of modern white spruce. White spruce, incidentally, both now and in the Pleistocene (Brown 1938) has cones which vary greatly in size between provenances and occasionally between families (Gordon, unpubl.). Incidentally, the associates of *P. banksii* were in general those of an eastern mixed forest, equivalents of jack pine, white pine, eastern hemlock, larch, alder, hazel (*Corylus*), butternut (*Juglans*) (Hills, L. 1969, pers. comm.) such as might be observed in parts of southcentral Ontario today.

Genecology in White Spruce

White spruce shows astonishing variation in crown form. Crown form, doubtless acquired through this species' long migrations as a consequence of the different environments and associates, is now regionally centred. Northern types tend to have crowns which are more linear and columnar; southern ones are usually more broad-crowned.

The important selection pressures would relate to whether or not this species grew in pure conifer stands of spruce or spruce-fir, or in mixtures with hardwoods, such as trembling aspen and white birch or tolerant hardwoods. There would likely be, for example, greater selection for broader crowns among those growing with hardwoods. Similarly, selection pressures would exist relating to whether snowfall was wet or dry, heavy or light; broad-crowned types tending to take the strategy of being able to hold snow up without breakage, narrow-crowned types tending to shed it. While narrow-crowned types do tend to be more uniformly distributed at higher latitudes, there are small populations of tall, narrow-crowned spruce existing as isolates at lower latitudes in the spruce range.

There are also several different types of crowns within the narrow and broad groupings. For example, Figure 23 shows an uncut face of a white spruce stand in Alaska. Of the crowns clearly visible in this picture, all but two are extremely narrow-crowned types, typical of interior Alaskan crowns. Two of them are somewhat broad relative to the others, but by southern standards, not broad.

Figure 24 illustrates an unusually narrow-crowned tree in central Ontario. This crown is sufficiently narrow that some would identify it as black spruce.

Very tall, narrow linear crowns of central Alaskan white spruce are shown in Figure 25. These crowns are so narrow that it leads less experienced people to call them hybrids of white and black



Figure 23. Interior Alaskan white spruce, tall narrow columnar-type crowns.

spruce or even simply black spruce.

A typically broad-crowned type is shown in Figure 26. This is in Site Region 5 of central Ontario in a north temperate forest. This type is very common in New Hampshire and central Maine. This crown type in Norway spruce is known as *bürsten-fichte* (Priehäusser 1958).

Figure 27 illustrates a broad, pendant-type crowned tree from central Ontario. All the twigs



Figure 25. Long narrow linear crowns of mature white spruce, interior Alaska.



Figure 24. Unusually narrow-crowned white spruce, central Ontario.



Figure 26. Broad-crowned white spruce, north temperate forest, central Ontario.



Figure 27. Broad pendant-type crown, north temperate forest white spruce, central Ontario.



Figure 29. Long linear-crowned, highly productive white spruce, central and northern Ontario.



Figure 28. Spike-type, north temperate forest white spruce, central Ontario.



Figure 30. Pollen collection in superior white spruce.

on this tree hang down. There are first and second order branching, but the second order branching is all pendant. More extreme forms of this crown type are commonly found in Norway spruce and are known as Kamm-fichte (Priehäusser 1958). This tree is broad-crowned and is growing with tolerant hardwoods and hemlock in a north temperate forest.

A 'spike-type' crown is shown in Figure 28. The bole is long and linear with a very narrow taper. There are first order branches going out from the bole but essentially no second order branches at all. There are many small third order twigs growing from, and pointing in all directions from, the first order branches. The crown has an excessively see-through appearance. This crown type also occasionally occurs in Sitka spruce (*P. sitchensis*).

Figure 29 illustrates a tall, linear-crowned tree, occurring in central and northern Ontario. It would be classed as a rather narrow-type crown but would be still broader than those in central Alaskan trees. This tree is a very desirable type for tree improvement work. Its height-to-diameter ratio is excellent: a long, linear tree with excellent crown form. Figure 30 shows pollen pickers at work in that tree.

With such wide variation in species such as white spruce, genecological questions such as the crown-type strategy are of considerable importance in breeding and tree improvement. These different strategies relate markedly to efficiency and productivity.

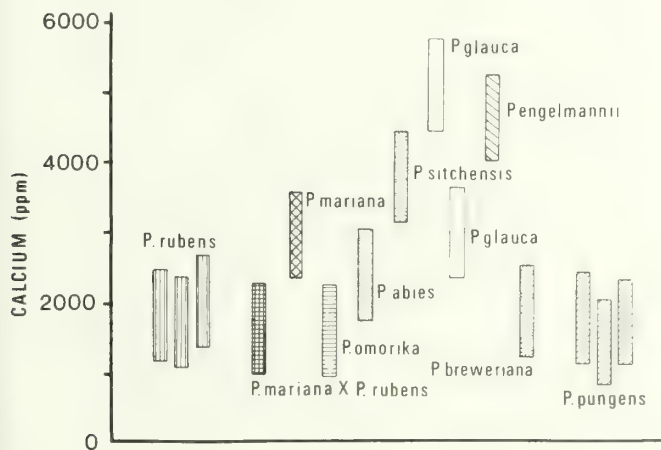


Figure 31. Calcium uptake of different spruce species and family sources, growing on a common, low lime landtype.

Another genecological consideration is nutrient uptake. Figure 31 illustrates calcium uptake in a number of species and family sources of spruce. For the sake of argument, they could be called 'genotypes' of the genus. These trees are growing in replicated plots in a *Picetum* in southcentral Ontario at latitude 45°30', and are all on the same landtype. The landtype is a deep fresh granitic till and moisture is not limiting. However, the only source of calcium is the granitic petrography, and lime concentrations in the soil are not high.

The different patterns of calcium uptake exhibited by various species groupings are of interest. Three populations of red spruce on the left are relatively similar. A black x red spruce hybrid family population is not different from red spruce, yet the uptake of calcium by a pure black spruce population is significantly greater than that of red in all but one population.

Serbian spruce (*P. omorika*), in its native sites in Europe, grows on limestone benches in the Dinaric Alps. In this *Picetum*, like red spruce, it is not taking up much calcium. This species may have a method of controlling calcium uptake or it may simply reflect the low calcium availability of this landtype. Calcium uptake in Norway spruce (*P. abies*) is a little greater but not essentially different from that of red. Blue spruce (*P. pungens*) and Brewer's spruce (*P. breweriana*) are at the same general level as that for red and Serbian. None of the populations of these species are taking up very much calcium, either demonstrating an ability to exclude it or the fact that it isn't available in the first place.

However, when the uptakes of Sitka, white and Engelmann spruces are considered, calcium availability does not appear to be limiting. There are two families of white spruce, one of them clearly taking up substantial amounts of calcium, even though lime supply in this landtype is not high. This is true for Engelmann spruce, and Sitka is not far behind. A second population of white spruce has lower uptake, about the same as for black spruce, but still in general greater than that of red, Serbian, blue and Brewer's spruces. Differences in uptake also are apparent for other elements not shown here (Gordon, unpubl.) demonstrating marked species differences in tolerances and uptake. This accounts to some degree for the exclusivity of some species growing on certain kinds of sites, and the more universal edaphic distribution of other species and populations within those species.

Nienstaedt and Teich (1972) have provided an excellent review of the genetic status of white spruce. Essentially, where white spruce comes in contact with Sitka spruce on the Kenai Peninsula of Alaska, and in the Skeena River Valley of B.C.; and where it comes in contact with Engelmann spruce in British Columbia, Alberta and Montana, there are extensive areas of introgressed populations of these species. Accounts of possible introgressive hybridization or even casual hybridization between white spruce and black spruce (Larsen 1965; Roche 1969) are unfounded, and are in sharp contrast to all artificial crossing information. A crossing table modified from Nienstaedt and Teich (1972) follows.

Table 4 sets down five categories of cross compatibility of white spruce with other North American and Eurasian spruce species. Introgression between Engelmann and Sitka spruce has already been mentioned. Crossing is relatively easy with Yeddo spruce (*P. jezoensis*), a Japanese species of two varieties. This species is somewhat similar to Sitka, but it differs from it in a number of characteristics and does not have the growth

Table 4. Cross compatibility of *Picea glauca* and other *Picea* species

Easy	Moderate	Difficult	Very Difficult	Failure
¹ <i>P. engelmannii</i> ⁺	⁴ <i>P. pungens</i>	⁸ <i>P. likiangensis</i>	¹¹ <i>P. mariana</i> ↔ <i>P. mariana</i>	
² <i>P. sitchensis</i> ⁺	⁵ <i>P. schrenkiana</i>	⁹ <i>P. mexicana</i>	¹² <i>P. rubens</i>	<i>P. chihuahuana</i> *
³ <i>P. jezoensis</i>	⁶ <i>P. smithiana</i>	¹⁰ <i>P. maximowiczii</i>	<i>P. koyamai</i> ?	<i>P. purpurea</i>
	⁷ <i>P. omorika</i>		<i>P. koraiensis</i> ?	<i>P. balfouriana</i>
			<i>P. bicolor</i> ?	
			<i>P. wilsonii</i> ?	
			<i>P. orientalis</i> ?	
			<i>P. glehnii</i> ?	
			<i>P. abies</i> ?	
			<i>P. asperata</i> ?	
			<i>P. meyeri</i> ?	
			<i>P. montigena</i> ?	
			<i>P. retroflexa</i> ?	

⁺Also introgression

*Consistent failure

?Hybrid reported by one worker, but attempts by all other workers have consistently failed (hybrid still unverified)

First successful crosses are indicated: 1. Larsen 1948; 2. Eklundh 1943; 3. Rehder 1967; 4. Wright (in: Santamour 1967); 5. Fowler 1966; 6. Fowler *et al.* 1976; 7. Oksbjerg 1953; 8. Jeffers 1971; 9. Gordon 1980; 10. Jeffers 1971; 11. Gordon 1980; 12. Bongarten and Hanover 1982.

characteristics of Sitka.

The second category, moderate, has four species in it. These are species with which successful crosses are possible but not with all clones, and in which there are some barriers. If they are open-pollinated, side by side, crossing is very infrequent, but may be accomplished artificially with some effort.

The third group, classed as difficult, are species which can be occasionally crossed with some clones, but there have been many attempts at artificial crossing which have not been successful.

The fourth, or very difficult, category are those species which have been crossed very rarely with white spruce. Only one or two workers have been able to cross white spruce with red. Other species in this list are very uncertain. Hybrids have been reported but there has never been any verification of any of them. In general, white spruce does not cross with Norway spruce, or its close relatives, *P. asperata*, *P. meyeri*, *P. montigena* and *P. retroflexa*. There has possibly been one artificial cross made between black spruce and white spruce, and there is one individual occurring in nature called the Rosendahl spruce (*P. glauca* x *mariana*) which is so far considered to be the only possibly legitimate example of a putative natural hybrid. Most consistently, failures have been endless in attempting to cross white spruce with the four species listed in the last column. However, several of those in the very difficult category could probably be legitimately moved over to the last column.

The information generated from work on hybridization is being used in studies elucidating

incompatibility, embryo inviability, hybrid inviability, crossability, homo and heterozygote phenomena, backcrossing phenomena, crossing frequency, ecological barriers, homeostasis, introgression, gene flow, genetic behaviour of sympatric and allopatric populations, genetic drift, genetic distance, heritability, quantitative population and ecological genetics, and many phases of tree improvement, wood quality, genotype x environment interaction, selection, propagation, etc.

Stand Dynamics of the Spruce-fir Forest and the Budworm (*Choristoneura fumiferana*)

The following stand structure and dynamics data (Figs. 32-38) illustrate and compare typical white spruce-fir stands in the boreal forest and typical red spruce-fir in the north temperate forest and show how the perpetuity of the spruce component in such stands is related to budworm events. The white spruce-fir example is in north-central Ontario, latitude 48°00', longitude 82°30', elevation 366 m; the red spruce-fir example is in southcentral Ontario, latitude 45°00', longitude 77°18', elevation 335 m. The data are based on a series of plots in areas that have had the customary historical budworm events of most eastern spruce-fir forests.

Figure 32 presents primary stand structure of the white spruce-fir forest. At this stage of development, there are typically low numbers of very large white spruce trees. There are moderate numbers (20 per hectare) of immature trees in each centimetre class between 10-20 cm, and fairly good numbers (200-50 per hectare) in the 5-8 centimetre classes, respectively. Fir, in contrast, have no trees greater than 15 cm. However, in the 5-8

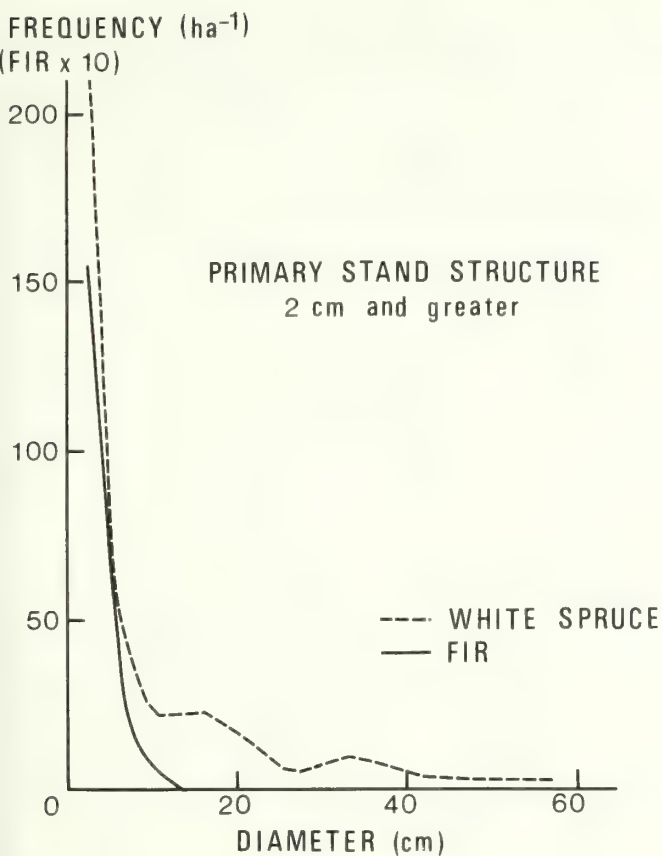


Figure 32. Primary stand structure, white spruce-fir.

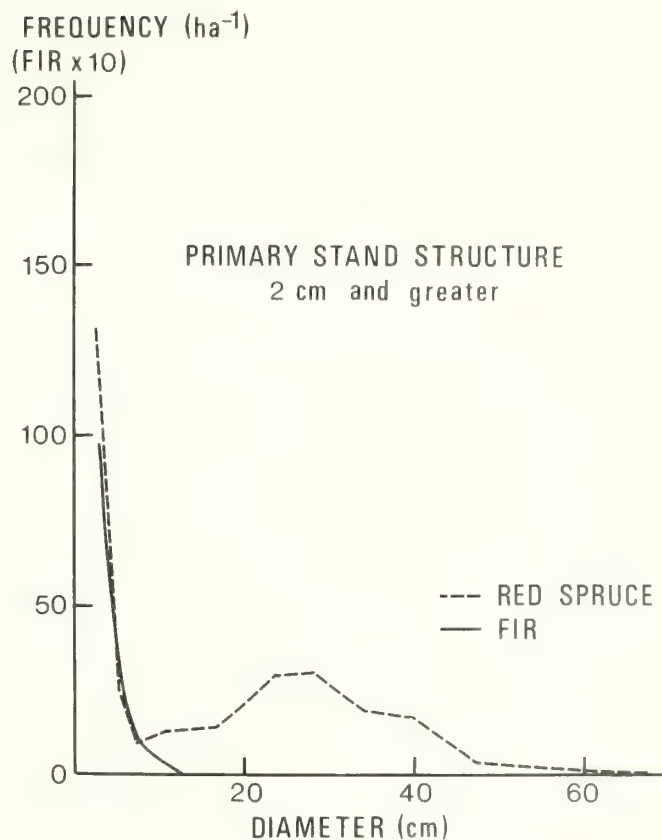


Figure 33. Primary stand structure, red spruce-fir.

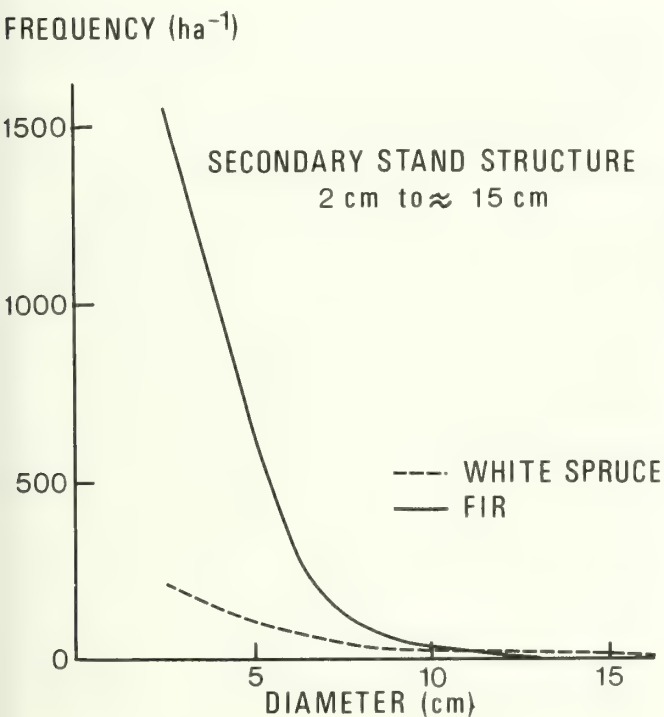


Figure 34. Secondary stand (rising understory) structure, white spruce-fir.

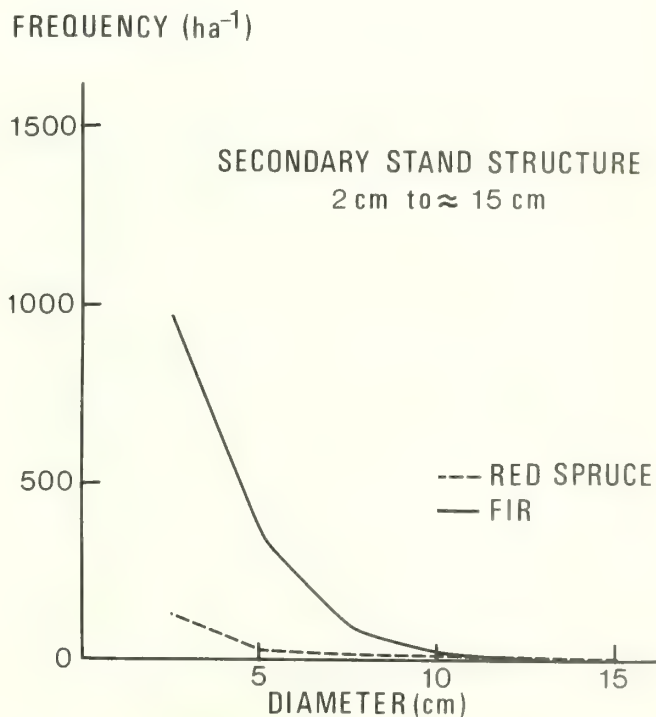


Figure 35. Secondary stand (rising understory) structure, red spruce-fir.

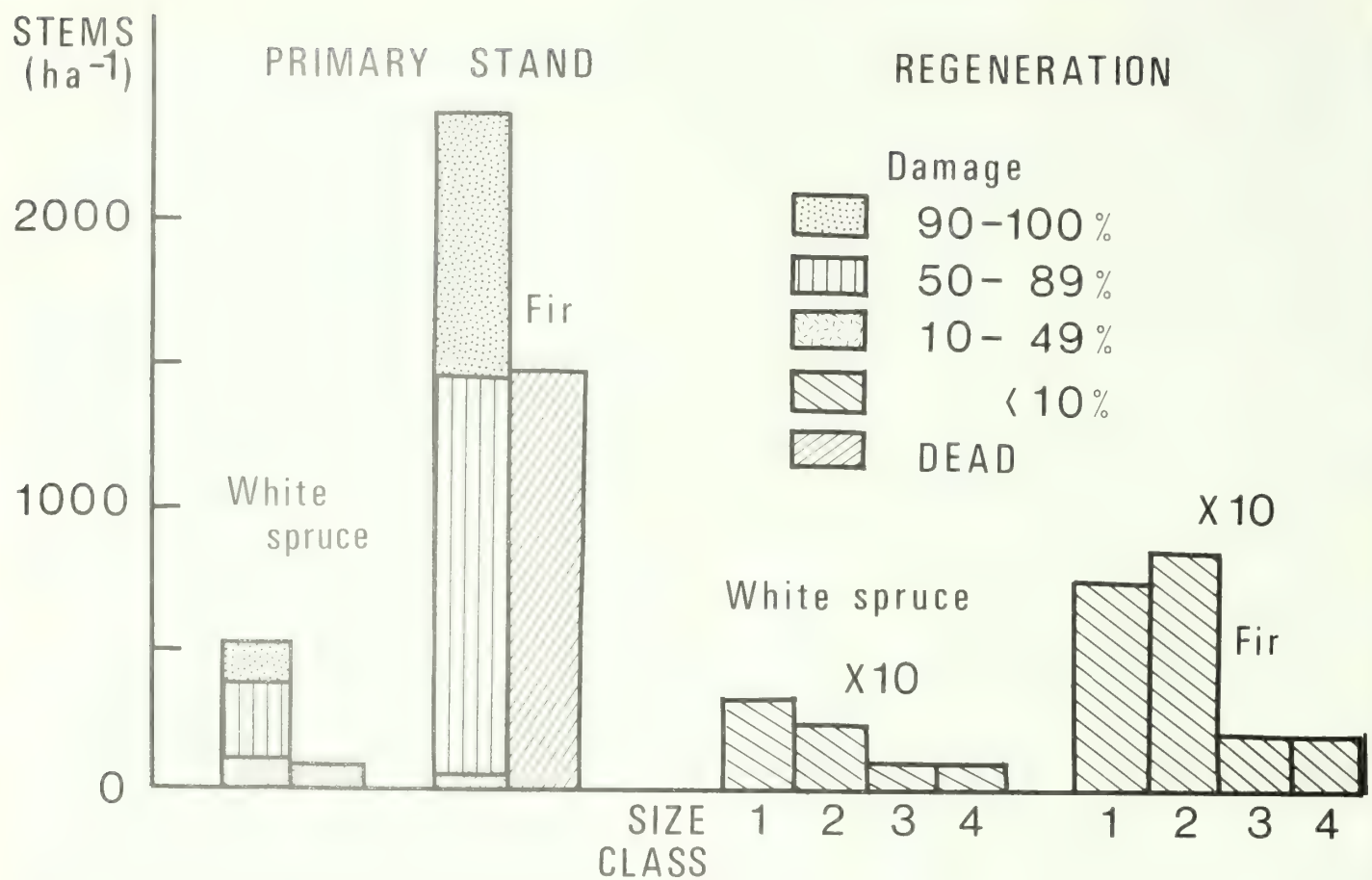


Figure 36. White spruce-fir stand structure (1979) following budworm attack. Primary stand includes standing dead, residual overstory, dead and damaged secondary understory.

centimetre classes, there are 1500 to 500 per hectare, respectively. This is a ratio of about 7:1 fir to spruce in the younger part of the stand. Such ratios commonly occur up to 10 or 12:1. The young fir are growing aggressively and, as expected, as this regeneration wave rises in the stand, the numbers of the small spruce will drop still further through competition from the fir.

Figure 33 illustrates the primary stand structure of the red spruce-fir forest. As in the preceding example, there are only small numbers of trees in the 45-65 centimetre diameter classes, and like the white spruce-fir stand, there are almost 20 trees per hectare in each of the centimetre classes between 10 and 20 in the red spruce-fir stand. Unlike the preceding stand, however, the red spruce-fir carry more individuals in the classes between 20 and 40 cm. This is compensated for by the slightly lower frequency in the 10-20 centimetre classes. Stands are roughly in the same state of development, however, and the fir has reached the 15 cm size class. The ratio of the fir to spruce in the rising regeneration wave in the 5-8 centimetre classes is about 8:1 fir to spruce. It is clear from this that as the small trees rise, the great preponderance of fir will be sustained and there will be some losses in the numbers of small spruce, again through competition with fir. In

both of the cases illustrated, it is clear that the ensuing stands will be very much dominated by fir.

Figures 34 and 35 permit closer examination of the secondary stand between 2 and 15 centimetre diameter classes. Ratios of fir to spruce remain relatively constant by diameter class as indicated in the foregoing.

Figure 36 illustrates the relationship between the primary stand and the residual regeneration developing under it in white spruce-fir. The primary stand here contains the residuals destroyed and damaged by the budworm and also the rising secondary stand trees comprising the large numbers of fir and the much smaller numbers of spruce in the ratio of 7:1 in the very small diameter classes (2-15 cm). It is these trees which it is expected will form the next stand.

However, the structure of the regeneration which has formed underneath the primary stand is of interest. Regeneration has been divided into four size classes from 3 cm in height to 2 cm dbh. Here again, fir dominate, but it is imperative to scrutinize the relationship apparent in the 3rd and 4th regeneration classes from 45 cm in height to about 2 cm dbh. The ratio of fir to spruce is markedly different. In these critical size classes,

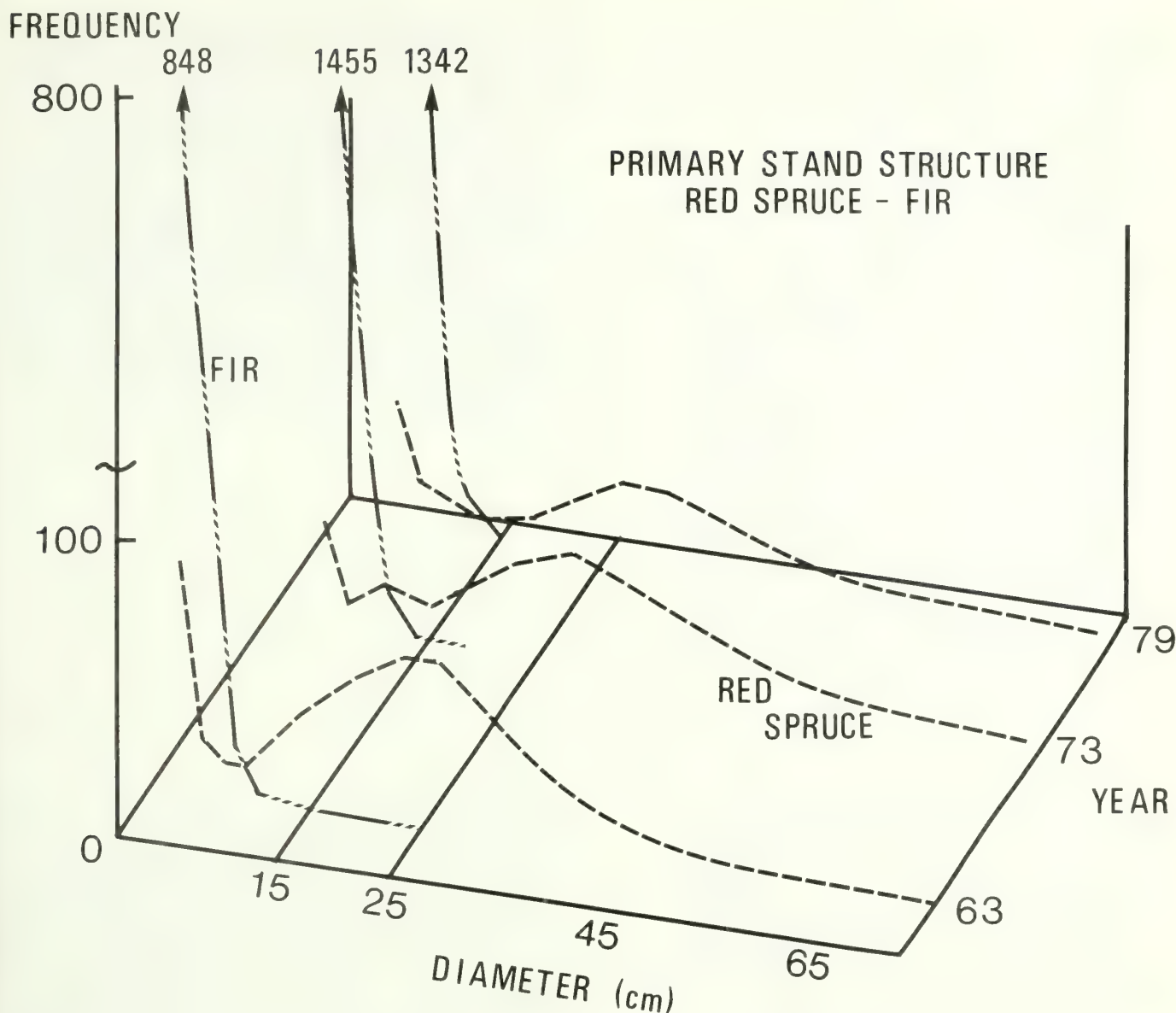


Figure 37. Red spruce-fir stand dynamics following the course of a budworm event.

the ratio is now 2:1 fir to spruce.

If the present overstory, including the rising secondary stand wave, were now wiped out, the stand would have a much more favourable composition of spruce relative to fir. The explanation for the shift in ratios in the regeneration is that despite the better seedling establishment characteristics of fir as compared to spruce, numbers of fir in the seed-bearing size in the original overstory have been totally eliminated by the massive preceding budworm event. This condition will prevail for many years, until such time as the rising wave of the secondary stand develops to a size which is consequent for flowering.

We have been privileged in being able to establish, monitor and work with data sets of long-term plots in spruce and fir. The great value of such long-term studies is clearly

demonstrated as time goes on. These plots were initially established in 1959 and 1960 and are yielding very interesting data, some of which follows.

Figure 37 provides a model of the red spruce-fir forest showing stand dynamics through 16 years. It may be seen that for spruce the modal portion of the stand advances in this time period from 15-25 cm. There have also been some losses in numbers of individuals in spruce in the modal portion of the stand.

In the secondary portion of the stand, from 2-15 cm dbh, there were some initial losses in spruce, but their numbers have been holding and recently increasing slightly. Changes respecting fir are interesting. In the modal portion of the stand, fir reached 25 cm in 1963, but with ensuing remeasurements in 1973 and 1979, while the numbers had increased somewhat, fir became restricted to

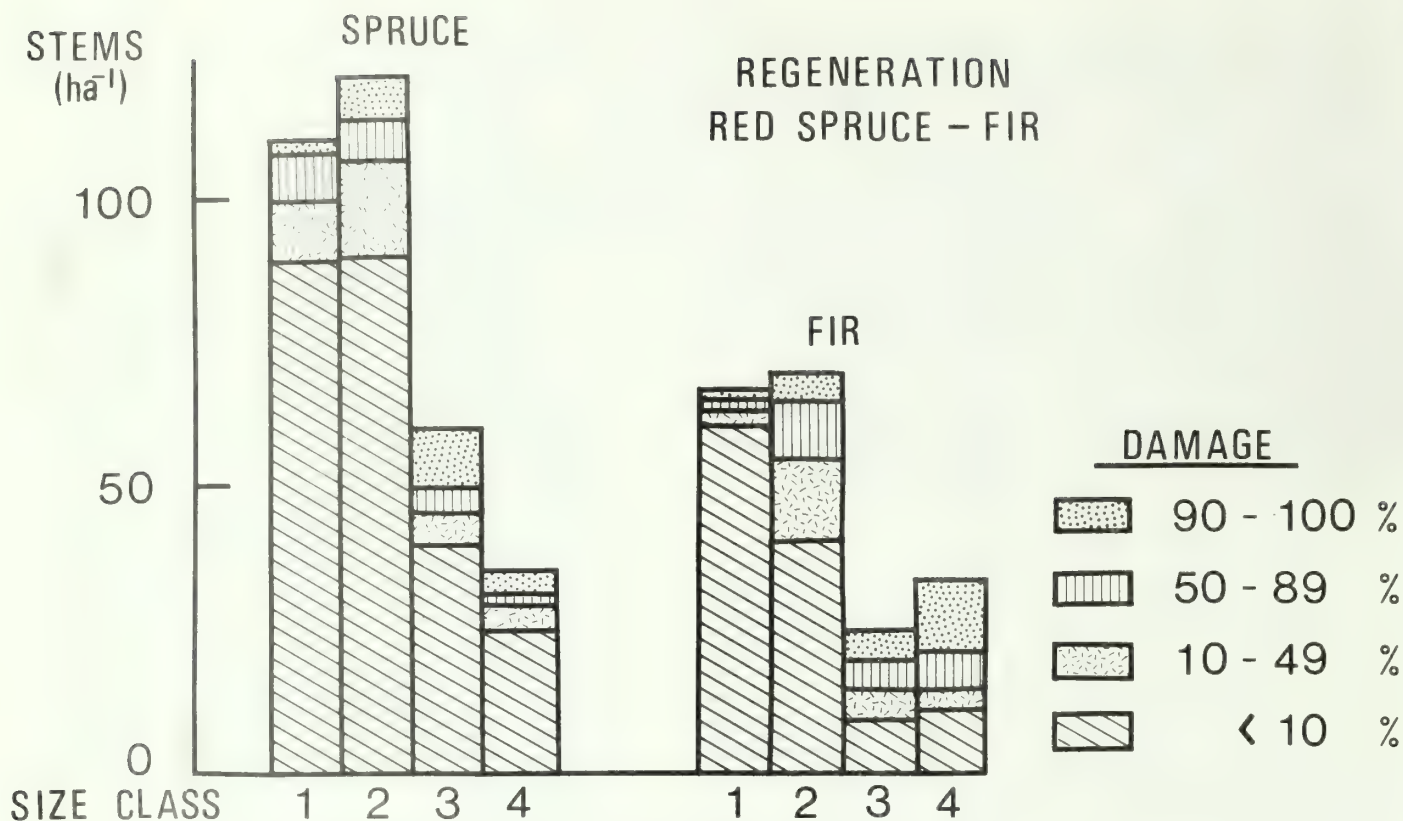


Figure 38. Red spruce and fir regeneration (1980) following a budworm event.

the classes below 15 cm, in fact, as we have seen from Figure 35, almost entirely to dbh size classes from 3-12 or 13 cm. The event which strongly influenced this stand development was a budworm buildup which initiated in 1971 and continued as a major outbreak through 1979.

Figure 38 presents data on the regeneration of the red spruce-fir forest. The regeneration is divided into size classes as above: the 3rd and 4th classes comprise seedlings from 45 cm to a metre in height, and one metre in height to 2 cm dbh. These are the most important in that they will be the size classes which, in most likelihood, will constitute the next stand. Damage categories are indicated, and what should be noticed are the differences in proportion of the budworm damaged to undamaged seedlings between spruce and fir. It may be seen that severely-damaged seedlings in the damage categories of 50% or greater, which will probably be eliminated as recruitment candidates for the future stand, constitute less than a quarter of both the 3rd and 4th size classes in the red spruce regeneration.

On the other hand, in the fir regeneration, more than a third in size class 3 and more than a half in size class 4 have been severely damaged and eliminated as recruitment candidates. The damage on the fir regeneration is twice as great as that on spruce in the last two size classes (3 and 4 combined) which, it will be recalled, are the trees now expected to enter the future stand. The higher numbers of spruce over fir in all regeneration classes is then an actual consequence

of the budworm outbreak initiating in 1971.

It was noted in Figure 37 that fir was entirely eliminated between 1963 and 1979 from the 25 cm down to the 15 cm class, and most of it to lesser classes than that. Budworm not only reduced the fir in the stand largely down to size classes below flowering size, but also they would have interfered directly with flowering in those that were large enough to have flowers.

Since this data was collected, the process has continued to be played out. Current data coming in indicate that the secondary understory stand has indeed been heavily affected by budworm and large numbers of the fir have been totally eliminated. On the other hand, the spruce in that segment of the stand have to a large extent survived, and are still intact and growing. It will be seen that it is not, then, as was originally expected, the rising trees of the secondary understory stand (2-15 cm dbh) which will form or will even be desirable to form the next stand.

Figure 39 illustrates the red spruce stand overstory in 1959 with some old fir chicos still collapsing, and the rising secondary stand underneath consisting of almost pure balsam fir. The intensity of the outbreak in the secondary stand understory is shown in Figure 40 taken 20 years later in 1979. There are still surviving red spruce overstory trees, some of them damaged, some scarcely so, but balsam fir has almost entirely been eliminated.



Figure 39. Detail of red spruce-fir stand (1959). Overstory of red spruce, rising understory of pure balsam fir.

Figure 41 shows the interior of the red spruce-fir stand in 1979. The entire rising secondary or understory stand of small balsam fir is here seen to be totally stripped. There are hardly, if any, alive.

Figure 42 illustrates detail of a secondary understory stand in 1979, largely balsam fir, very heavily damaged or dead. A few still have some green foliage. A small red spruce about 1.5 metres high, and a single balsam fir about a metre are to



Figure 41. Interior of red spruce-fir stand. Rising secondary fir stand all stripped and dead.

be seen in the foreground in the rising regeneration class with very little damage and long well-developed leaders. The overstory red spruce are still fairly well intact. The red spruce in the secondary understory stand, about 5-8 metres in height, are alive and growing well.

In both the foregoing cases, the white spruce-fir and the red spruce-fir, a secondary budworm event has been substantially responsible for the maintenance of the spruce in the forest. Similar interpretations can be clearly deduced from the case history inventory data for the state of Maine



Figure 40. Red spruce-fir stand (1979). Red spruce overstory still surviving, balsam fir understory secondary stand all dead.



Figure 42. Detail of secondary understory red spruce-fir stand. Balsam fir all dead or dying; healthy red spruce regeneration dominating.

(Powell in press). I would propose that there are strong arguments for the co-evolution of the spruce budworm and the spruce-fir forest, and that where spruce and fir grow together, budworm are an essential factor in maintaining spruce in the stand through time.

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STRESS AND DEATH OF TREES¹

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Abstract.--Trees survive after injury and infection so long as they set effective boundaries to resist spread of pathogens. Boundary-setting is beneficial so long as the volume of walled-off infected wood is small and the intervals between infection are long enough to allow enough new cells to be generated in new spatial positions that can hold enough energy reserves to maintain the tree. A tree may be able to trap solar energy, but when space for energy storage has increased, all systems of the tree begin to diminish. Many secondary agents then attack. Fighting the secondary agents will not solve the basic problem of energy depletion, or stress, that they progress to irreversible strain and death. Answers to the basic problem of poor tree health will come only when tree management decisions are made on the basis of a much better understanding of the tree. Needed now is a new attitude about trees.

Introduction

Stress and death, and gloom and doom, are major current topics associated with forests worldwide: diebacks in Australia, exploitation of the tropical forests, large-scale dying of forests in Europe, dying of young planted forests in Korea, and, of course, all types of forest problems in the United States, and the list goes on and on. Is this recent attention to our world forests a media exaggeration, or do we really have some serious problems in our world forests? Are any forests of the world really in a state of stress and death?

During the last several years I have had opportunities to examine trees in several other countries. Some forests are very healthy; many are not.

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A common thread that runs through many of the global tree problems is poor tree health. Insects and microorganisms are always present and are blamed for the problems, but I doubt that they are the causes or starting points of many of the tree problems. The organisms are often secondary agents. Too often we fight the secondary agents or the symptoms rather than the causes. And, even if we are successful in eliminating one group of secondary agents, another group will be ready to start.

A great advancement for humankind came about when the benefits of health were realized. It is better to concentrate on what keeps you healthy rather than on what makes you sick. Medical science advanced when bodies were systematically dissected. Then immunization treatments were used to make the body's own defense system function to keep disease at low levels. We must keep these points in mind as we discuss tree health problems. We should also concentrate on what keeps trees healthy rather than on what makes them sick. We should have a clear understanding of how trees are constructed and how they function. And we must help trees help themselves to use their defense systems more effectively.

There are some basic reasons why poor health is a major tree problem. Ignorance of tree basics is the major worldwide problem. We desperately need an attitude change about trees. Trees cannot sustain repeated abuse without serious injury. Trees do die! Decay is not a natural process beyond our limits of regulation. We can reduce the amount of rot. Many of the inaccuracies about trees that are being taught and are deeply entrenched in textbooks must be adjusted (Shigo 1980, 1982a, 1982b). We can start by learning about trees. This is not to say that anyone was or is wrong. It does mean that science advances as adjustments are made on the basis of systematic reexamination. Indeed, it is time to reexamine a tree: how it is built up, how it functions to stay built up, and how it eventually breaks down.

Some Tree Myths

Do you still believe that frost starts the long deep cracks that are called "frost cracks"? Do you still believe that wind starts the circumferential cracks called "wind shakes"? That trees heal wounds? That trees absorb minerals selectively from the soil to form mineral streaks? That heartwood is an unreactive tissue? That flush pruning is the best way to remove branches? The list goes on and on. My point is that if you believe these myths, and the many others **that** are in textbooks, it is no wonder that proper management schemes cannot be developed to produce high-quality trees that will produce high-quality products.

It is far beyond the scope of this paper to discuss the many misconceptions about trees, treatments, and factors affecting defects. I shall discuss the role of energy reserves in the tree defense process. Excellent information on starch reserves in trees has been given by Wargo (1971, 1975, 1976, 1979).

Some Definitions

First it is absolutely necessary to define some terms. Voltaire said to define your terms and arguments will be less than a few minutes. These are my definitions, and it is doubtful that you will agree with them totally. They are terms that are used commonly by many people, but seldom defined. This is why there are so many arguments.

HEALTH is the ability--dynamic state--to resist strain. STRAIN is an injurious, irreversible condition caused by excessive stress. STRESS is a gradation of events resulting in a drain, blockage, disruption, or shunt of energy. ENERGY is fuel or the force that "runs things" or maintains vitality. VITALITY is the dynamic ability to grow and reproduce within the limits of vigor. VIGOR is the intrinsic genetically controlled capacity--potential--to survive after injury and infection. INFECTION is a process of energy transfer from host to pathogen. PATHOGEN is an agent that causes injury or strain to a host as a result of energy transfer. Organisms that decay trees are pathogens because pathogenesis is based on the entire organism and not on its parts. DISEASE is a process of energy transfer to pathogens from the host that results in a condition of strain to parts of the host or the entire host. HOST is the organism that has the stored energy and is interacting with a pathogen in energy transfer. ENERGY TRANSFER must consider the three laws of thermodynamics: (paraphrased here for emphasis) 1) you can never win, only break even, 2) you can only break even at absolute zero, and 3) you can never reach absolute zero.

Indeed, we cannot win them all, but we can surely win more than we are at this time.

How Do Trees Die

Trees, like other organisms, die three ways: dysfunction, infection, and mechanical disruption. There are many variations on these themes, and usually the variations overlap many times before death. Dysfunction occurs in many ways when tissues do not function properly. For example, this can occur when soil water is too high or too low for the tree, or when microelements or pH, or soil type, or any number of factors change or are changed. Trees can adapt to many conditions if they have the time. Any sudden change may make adaptation impossible or difficult. Tree problems associated with dysfunctions are least or poorest understood because they usually are

not recognized until it is too late. We know so much about ends of processes, but so little about beginnings. Yet it seems that secondary agents can rapidly recognize the beginnings of the unhealthy condition when they attack. Tissue dysfunction affects not only growth and reproduction processes, but also the defense system. To be alive but defenseless is indeed the worst condition.

The real problem with dysfunction is that additional energy may not help the condition. Indeed, dysfunction is the malfunction of some vital tissue, organ, or process. Adding more energy or more fertilizers may not help a malfunctioning tissue or organ. In fact, some treatments, such as over fertilization, may actually make the malfunction worse. Disruption of sites by logging, mining, agriculture, and grazing will cause poor tree health: stress, strain, and death. Misunderstandings of tree problems also lead to planting the wrong tree in the wrong place (conifers on hardwood sites)--done repeatedly in Europe--and any number of disruptions that alter normal tree functions.

A major problem in understanding trees is that we have borrowed too many terms from other disciplines, especially human pathology. We then try to fit or force the terms onto the tree, and they often do not fit. A tree can have many large dead and dying branches, but also an equal number of very healthy branches. Is the tree half healthy or half dying and dead?

In a sense, trees are multiple plants, or communities of plants. The parts may die, and new parts are generated in new spatial positions. Or, the entire community may be in trouble. The dysfunction or infection may be affecting a part of the community, or the entire community of trees. We lack proper terminology to discuss clearly such an organism or "group of organisms."

Add to this the problems of mechanical disruption. The unique characteristic of a tree is its mechanical support system. Trees are still the biggest organisms ever to inhabit this planet. Trees have evolved unique ways to protect their mechanical support systems--they set boundaries to resist spread of pathogens. But, when a pathogen digests the support system, and the tree falls over, the tree is dead. This is why decay-causing organisms are pathogens.

In a sense, trees "attempt" to avoid some of the problems due to size by regulating generating with shedding. Trees by nature of the growth systems do get larger every growth period. But, trees regulate this somewhat by shedding twigs, branches, support roots, and absorbing roots that begin to age and die.

How a tree dies is not a simple matter. The more we know about how trees live, the more we can do to keep them from dying.

Energy

Energy is the fuel or force that maintains the biological machine. Trees get energy by trapping solar energy in a molecule of carbon dioxide and water. Of the 0.1% of solar energy trapped by all organisms on this planet, trees trap 50%. The energy is used as sugars and stored as starch, oils, and other materials. The energy maintains growth, reproduction, and a defense system. Insoluble energy reserves, mainly as starch and oils, are used to start the tree processes after dormancy. It takes a great amount of energy to maintain and operate a defense system. The other requirement is space for the needles and leaves to trap energy. Survival requires space and energy.

Energy and Boundary-Setting

To summarize to this point: Trees are highly compartmented, woody, perennial, shedding plants that are usually (but not always) large and single-stemmed. Trees generate new cells in new spatial positions and shed dying and dead parts. Trees do not restore injured and infected tissue. Trees do set boundaries to resist spread of pathogens--compartmentalization (Shigo and Marx 1977, Shigo 1979, Shortle 1979). A model of compartmentalization is called CODIT.

CODIT

To understand defects from the tree to the product it is absolutely essential to understand boundary-setting processes. To make this very complex subject clear, a model called CODIT was developed (Shigo and Marx 1977). CODIT is an acronym for Compartmentalization Of Decay In Trees. The model has two parts. Part I is in the tree at the time of injury and infection. Part I is represented in a model sense by three walls: walls 1 resist--not stop--vertical spread of the microorganisms, walls 2 resist inward spread, and walls 3 resist lateral spread. In a sense, the tree attempts to wall off the microorganisms to as small a volume as possible, while the microorganisms counter this attempt by spreading as far as possible, as rapidly as possible.

After injury and infection, the still-living cambium about the injury begins to form a new tissue called the barrier zone. The barrier zone is a very protective tissue, but a very weak structural tissue. The barrier zone is a weak conducting tissue. In the CODIT model this separating boundary is called Part II, or wall 4. Wall 4 is where ring shakes and radial splits begin. Wall 4 may form after wounds or the death of branches and roots.

Trees survive after injury and infection so long as they have the time, energy, and genetic capacity to recognize and compartmentalize injured and infected cells effectively, and then generate enough new cells in new positions to continue to maintain the tree. The new cells

must be able to store sufficient energy to maintain growth, reproduction, and a defense system.

When energy is decreased, trees reduce growth and reproduction. When decreased energy reduces the defense budget, a high-risk situation begins. The risk is reduced when no further injuries are inflicted. But, when injuries are inflicted, the risk increases, especially when energy-drains caused by injuries and stresses repeat at shorter and shorter intervals.

The two important parts to energy reserves are: (1) the tree must have enough healthy needles or leaves in enough proper spaces to trap sufficient energy, and (2) the tree must have some place to store the energy reserves. This second requirement is often not considered. The second part also is counter to boundary-setting or compartmentalization.

Genetics of Boundary-Setting

The tree defense system is centered about boundary-setting. Trees that have the genetic program to resist spread of pathogens will limit the infected zones to small volumes (Garrett et al. 1979, Shigo et al. 1977, Lowert and Kellison 1981, Schmitt et al. 1978). Trees that have weak boundaries will have large volumes of infected wood. Compartmentalization is indeed an effective defense system when it functions to limit infected tissues to small volumes, and when the injuries and infections are not repeated within short periods. When more and more tissues that normally hold energy reserves are walled-off, the potential volume of wood for storage of reserves begins to decrease.

Starting Points for Infection

The three basic starting points for infections are: dying roots, dying branches, and mechanical injuries. It is impossible for a tree to grow in a forest without having some or all of the infection courts. Trees with strong genetic programs can wall off dying branches and roots effectively, and no volume of trunk wood is lost to the pathogens. When mechanical wounds are inflicted on the trunk, the tree responds to resist spread of the pathogen within the wood present at the time of injury, and then the tree forms a protective barrier zone that separates the infected wood from the new wood that continues to form.

As energy reserves decrease, the defense budget also decreases. The boundary-setting process is less effective. As new infections start, they spread faster and farther. When healthy wood is "trapped" between new infections and an older internal defect, the new infection will often spread rapidly into the "trapped" tissues.

The process of boundary-setting then begins to be a problem for the tree rather than the answer to survival.

Paradox of Boundary-Setting

One irony of the way natural systems operate is that a feature or characteristic of the system may be beneficial or destructive depending on the concentration of the feature, or characteristic--too little compartmentalization, too much compartmentalization--and timing--compartmentalization when energy reserves are high is beneficial, compartmentalization when energy reserves are low may be destructive.

The tree must produce new cells in new positions during the growing period or it ceases to be a tree. Energy is required for these functions. To compensate for lower energy reserves, the tree walls off more of its parts. But, when more and more branches are walled off, so are leaves and needles that trap energy. At this stage there is little hope for survival of the tree. Even if treatments could retain needles and leaves, and even if needles and leaves could trap an abundance of energy, there would not be enough space within the tree to store energy.

Long before a tree exhausts its energy supply, many weakly parasitic or opportunistic organisms attack and drain the remaining energy reserves. So, it is unrealistic to think that a tree will die because it exhausts its energy supply.

Aging and Boundary-Setting

When trees are young, 100% of their volume can be used for energy storage. The living cells in the wood store the energy reserves. As branches and roots die, and as injuries are inflicted, and as living cells in the wood die, the ratio of stem volume to volume of wood capable of storing energy reserves begins to decrease.

The tree regulates crown size and root mass by setting boundaries between aging, dying, and dead parts, and still living, healthy parts. The boundaries are usually effective in resisting spread of the microorganisms from the dying root or branch into the healthy wood. It seems that boundary-setting at the branch bases and root bases is under genetic control. When the microorganisms are aggressive, they may spread beyond the boundary and into the healthy wood. The tree usually responds by setting new boundaries deeper into the wood. The new boundaries may resist further spread and limit the microorganisms to small volumes of the joining stem or root. In other instances, the microorganisms may be even more aggressive and may breach the second boundary and spread into the trunk or the major root. The tree will still respond by resisting spread within the trunk or root, but also the tree does form a barrier zone that usually confines the infection to the trunk or root tissues present at the time the branch or root died.

How many boundaries are breached or broken may be a factor of aggressiveness of organisms, or it may be a factor of the tree. The tree may be a genetically weak tree that sets weak boundaries, or the tree may be an energy depleted tree that cannot set strong boundaries.

A young tree may be a genetically strong compartmentalizer, but as more and more branches and roots die, and as more and more injuries are inflicted, the boundary-setting capacity of the tree begins to decrease.

Once boundary-setting reduces the volume of wood that can hold sufficient energy to some yet unknown low point, the tree becomes strained. Once the tree is strained, the recovery is less and less likely.

Stress and Strain

A tree can have a great amount of stress without having strain. Stress includes all the dying branches, dying roots, and mechanical wounds. So long as the tree is able to collect and store sufficient energy, it will continue to grow and reproduce.

Stress also increases as dysfunction increases. Dysfunction of vital tree processes may be a genetic factor that becomes obvious very early in the life of the tree--usually leading to early death--or a factor associated with intrinsic genetically controlled aging processes. Dysfunction may also be associated with environmental factors such as discussed earlier, and also with some types of infections. Regardless, dysfunction results ultimately in an energy blockage, shunt, or drain, which is stress. And, when stress continues, strain may result.

Here are some important specifics about spruce and fir, based on my discussion on stress and strain.

Spruce, Fir, and CODIT

Fir has a very weak CODIT, Part I (Tippett and Shigo 1981, Tippett et al. 1982). What does this mean, especially for products? After branch death, root death, or mechanical wounds, the wood is rapidly invaded by microorganisms (Shortle and Ostrofsky 1983). But the tree produces very strong walls 4. In roots such a response permits the tree to remain alive with hollow roots, but the support function of the roots is greatly decreased. When such rot problems develop in large support roots that join at the tree base, a crack usually develops between the two joining roots. The vertical crack may extend far upward on the trunk. Cracks at the base of fir are reliable indicators of root rot, especially those caused by Armillaria mellea (Shigo and Tippett 1981).

As roots die in fir, and as microorganisms invade the wood within Part I, the wood may develop into wetwood, or either white rot or brown rot. Large columns of wetwood often develop upward into the trunk from dying roots (Schütt 1981).

New electrical methods have been developed to detect wetwood and decayed wood in fir and spruce (Davis et al. 1980, Blanchard et al. 1983). These methods make it possible to determine the width of sound wood, and to determine whether wetwood is present.

Spruce has a stronger Part I CODIT than fir. For this reason the columns of defect are usually smaller and end more abruptly in spruce than in fir. Ring shakes are common in spruce, but basal cracking is not as common in spruce as in fir. Spruce does not have as much wetwood. But spruce often has more problems with fungi associated with branch death. *Fomes pini* is common in spruce. Spruce seems to resist such infections very well until the number of infections becomes overwhelming, then the decay processes develop rapidly to form large central columns of defect.

What Can Be Done?

Excessive logging damage must be stopped now! Logging wounds--roots, trunks, branches--are major starting points for many types of defects including long cracks commonly called frost cracks. Frost does not start the cracks, wounds do (Butin and Shigo 1981).

Pruning practices must be adjusted now. Cuts behind the branch bark ridge and the injuries to the branch collar start many types of problems, including blue stains, ring shakes, vertical cracks, and cankers. Proper pruning (Shigo 1982a) does not mean leaving a stub, but the small branch collar must remain on the stem. If trees are pruned at an early age, this slight bulge will not reduce the width of clear wood for boards. But if the collars were removed, cracks and internal defects will form. Add to this the sawing of boards which contain the pith, and the splits will break outward, or the wet pockets associated with the branches will make drying difficult.

A logging wound reduction program must be started. Operators of machinery must be made aware of the damage that can result from wounds on the roots, trunks, and branches. Excessive logging damage must not be tolerated.

Decide whether the site will support high-quality trees. Measurements of cambial electrical resistance may help in making this decision.

Highly defective trees should be removed. Trees with basal cracks, especially balsam fir, should be first. If many cracked trees are growing on one site, it may be a root rot site, and the likelihood of growing quality trees there would be remote.

Know what you have on inventory plots. Use the Shigometer to determine internal condition of select trees. Use the Shigometer to help determine vitality of the trees.

Such a program involving removal of defective trees, thinning, proper pruning, and reduction of logging wounds on sites that will support high-quality trees, and the use of the Shigometer could result in a great increase in tree quality in a relatively short time.

Defective trees in our forests are primarily the result of long periods of high grading, taking the best and leaving the worst. In many of our forests, only the worst trees remain. It can be argued whether these trees are really genetically weak or tough trees, and that if given a reasonable change, whether they would grow into high-quality trees. I doubt this.

In an experiment involving deep drill bit wounds in sugar maples, paper birch, and yellow birch, selected as superior for growth rate and form, only a few of the trees were designated as strong compartmentalizers based on the volume of defect associated with the experimentally inflicted wounds.

At the same time we know from these studies and from other studies by our cooperators and other researchers that some individuals of a species are very strong compartmentalizers; they do limit defects to very small volumes. Studies on several species show that resistance to spread of decay is under moderate to strong genetic control (Shigo et al. 1977, Garrett et al. 1979, Schmitt et al. 1978, Lowerts and Kellison 1981). Genetic control is the key to future high-quality forests. We must increase our programs to select strong-compartmentalizing trees, and also to find faster and more accurate ways of identifying tough trees.

Biochemical enzyme markers may be a way to do this. Wounding studies are being done now on many species of conifers and hardwoods. Studies are also being done on very young trees to determine whether tough trees can be selected very early.

Conclusions and Warning

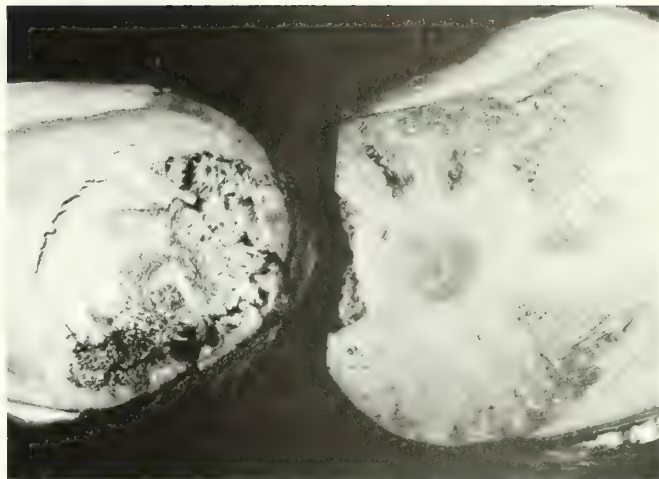
The worldwide pattern of poor tree health leading to many types of forest problems must be reversed before it is too late. Scientists must turn their attention to starting points of the problems rather than to the symptoms, secondary agents, and ends of the destructive processes. We cannot change decades, or even centuries, of mistreatment of our forests in a few years. We all share an education responsibility. We must make certain that decisions on our forests come from properly conducted experiments with controls. Learn what a tree is and learn how it functions to survive. Then let us help the tree help itself to survive in a healthy state. If we do not follow such a course, the fight against symptoms and secondary agents will continue, while more of our world forests die.

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Armillaria mellea is a major cause of root rot in spruce and fir.



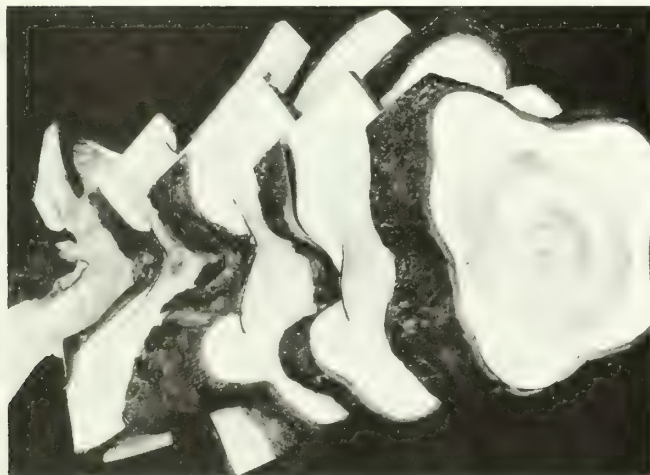
Two patterns of basal rot associated with *A. mellea*; left, center sound, right, decay advanced into the center.



Base of fir showing advanced decay associated with *A. mellea* between the roots.



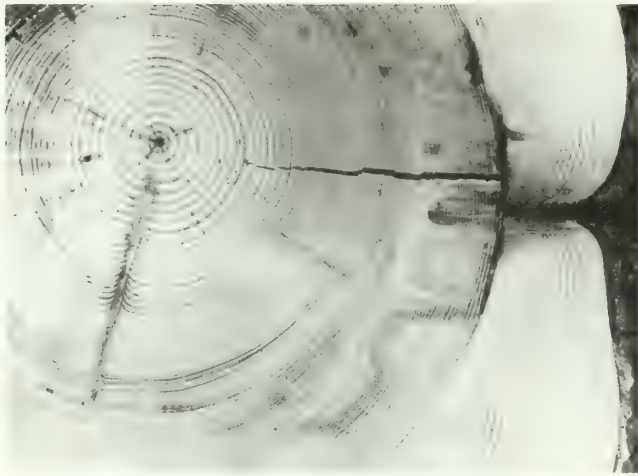
A proper pruning cut, left, and an improper flush cut, right, on a red pine after 2 years. Cuts should not be made behind the swollen collar at the branch base.



Basal sections from a fir show wetwood associated with root rot.



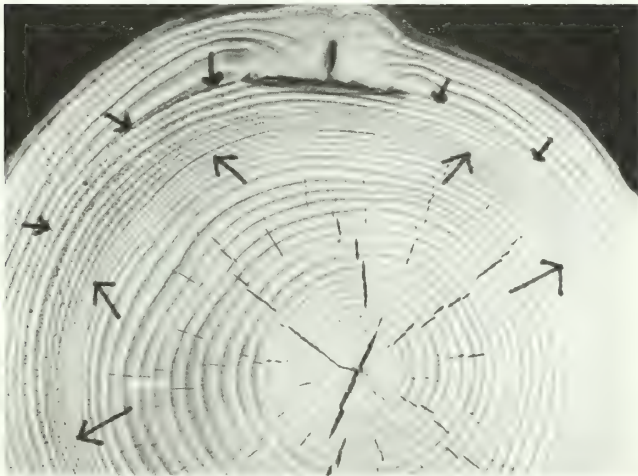
Dwarf mistletoe on red spruce can cause brooming, swollen trunks, and general decline of trees.



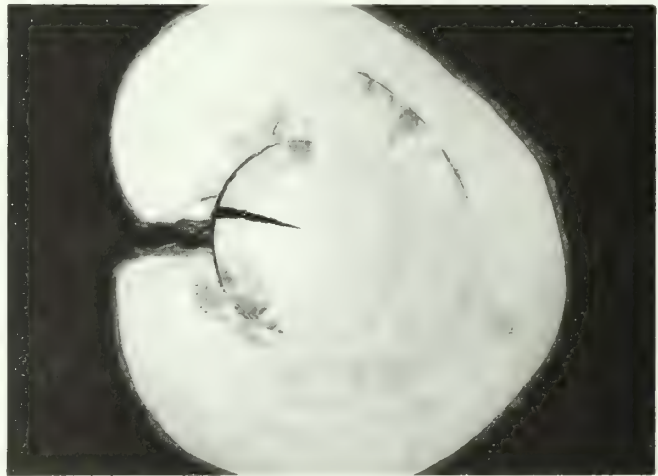
Wound on red spruce. Logging wounds are major causes of defects.



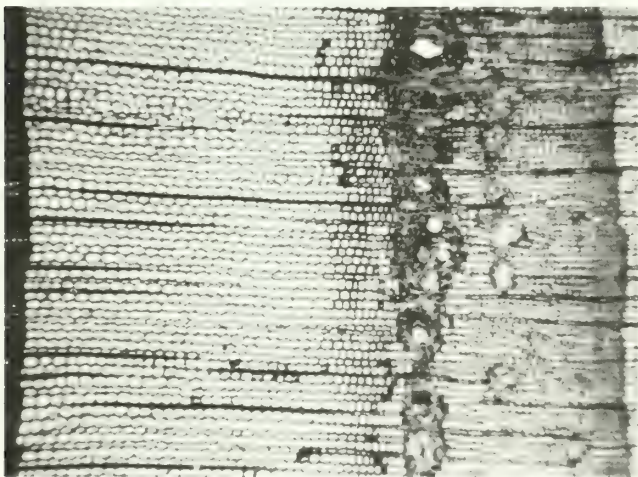
Ring shake in red spruce. Barrier zones associated with wounds and dead branches often start the shakes.



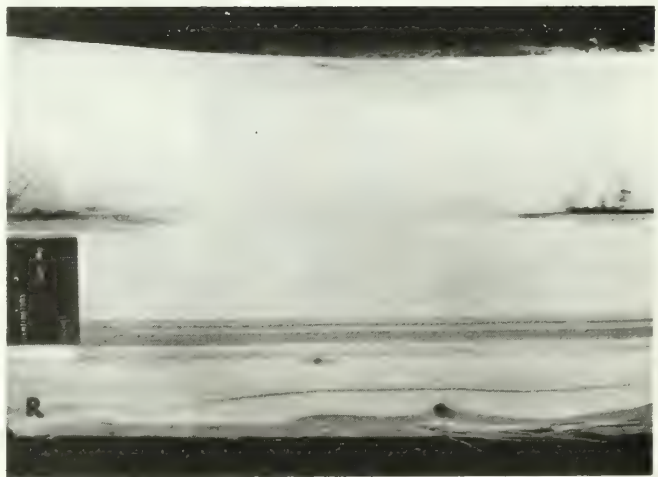
Small wound on Norway spruce. Small arrows show that barrier zone that formed after wounding. Large arrows show inward limit of resin ducts. Note lack of resin ducts behind wound.



Two major wounds in this red spruce limit its use for quality timber.



Microscopic view of the barrier zone 2 cm left of wound shown above. The barrier zone is the starting point for most of the shakes in trees.



The 2 small wounds in the red spruce sample are the starting points for ring shake.

DYNAMICS OF THE FOREST AND EASTERN SPRUCE
BUDWORM OUTBREAKS

D. Gordon Mott

The temporal and spatial characteristics of the Eastern Spruce Budworm outbreaks since 1900 are evaluated qualitatively. Hypotheses concerning the role in epidemic dynamics of forest character, coupled with climate, density dependent populational processes, aerial forest spraying, and dispersal are offered. Speculation about future events and the roles of forest management and protection is indulged.

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Three topics are discussed: our research and development program, the Michigan Impact Plot System (MIPS), and technology transfer. We describe the MIPS and our techniques for quantifying impact of the spruce budworm in the Hiawatha and Ottawa National Forests. We summarize percent mortality, total dead volume, live basal area per acre, dead basal area per acre, and defoliation rankings from sampled spruce-fir stands. Recommendations are made for future studies on forest damage assessment.

Introduction

The spruce budworm, *Choristoneura fumiferana* (Clemens), was not considered a major problem in the Lake States until recent years. More intensive forestry practices and greater market demand for spruce and fir have been partially responsible for the increased interest in techniques to measure and reduce impact of the spruce budworm in spruce-fir stands. Lake States land managers have been seeking additional information on the spruce budworm since the mid-1970s.

Over 2.5 million acres of commercial forest in Michigan are classified as spruce-fir (Montgomery et al. 1983c). The most recent spruce budworm outbreak was reported in the eastern part of Michigan's Upper Peninsula in the late 1960s, with mortality first observed in 1971. Heavy defoliation and considerable tree mortality occurred during the 1970s (Witter et al. 1984). The spruce budworm population dropped to fairly low levels during 1981 throughout most of the Upper Peninsula. Tree mortality occurred in 1982 and 1983 in stands that were heavily defoliated during 1978 to 1980 because mortality continues for one or two additional years following the end of an outbreak. Very low population levels were noted in 1981 and 1982, but in 1983 budworm populations increased in many areas. Noticeable defoliation occurred in the central Upper Peninsula during 1983.

There was very little information available in 1977 on the impact of the spruce budworm on spruce-fir stands in Michigan. With this in

mind, a seven-year study was designed. Entomologists, foresters, biometricians, remote sensing specialists, computer specialists, economists, and technology transfer specialists were involved in this research. This paper will focus on three topics: our research and development program, the Michigan Impact Plot System, and technology transfer.

Research And Development Study Design

Studies to assess widespread damage to forests (by insects, diseases, and other agents) are very expensive and time consuming. We economized by concentrating our efforts on four major objectives that interacted and could be worked on simultaneously. Our objectives were to quantify the impact of the spruce budworm on spruce-fir stands in the Ottawa and Hiawatha National Forests, to develop techniques for measuring impact, to develop hazard-rating systems for spruce-fir stands in Michigan's Upper Peninsula, and to provide forest managers with pest management information, especially related to impact.

The study proceeded through the following steps:

1. Review existing literature and discuss proposed research ideas with other researchers and land managers (1977, 1978).
2. Determine long-term research objectives (1977-84).
 - a. Quantify impact (1978-84).
 - b. Develop techniques for sampling impact (1978-84).
 - c. Develop hazard-rating systems (1978-84).
3. Develop study plans (1977, 1978) and submit grant proposals (1978-83).
4. Establish (1978, 1979) and evaluate (1978-84) the Michigan Impact Plot System.
5. Develop (1978-81) storage capabilities, computer programs, and mapping routines for the impact data collected during 1978-84.
6. Design and implement additional research studies to meet the objectives of this project (1979-83).
 - a. Sampling size (1979).
 - b. Remote sensing (1979-81).
 - c. Regeneration (1980).
 - d. Site classification (1982).
 - e. Economics (1983).
7. Analyze data and develop final products (1979-84).
8. Determine new priorities and finalize studies for the next field session (winter prior to each field season).
9. Participate in user group meetings (1978-84).
10. Publish techniques and results from research studies (1979-84).
11. Develop and implement a technology transfer program (1981-85).
 - a. Needs assessment survey.
 - b. Manuals and handbooks.
 - c. Remote sensing workshops.
 - d. Evaluation of processes and products.

Methods

The Michigan Impact Plot System (MIPS) was established in the Hiawatha and Ottawa National Forests (Fig. 1) during 1978 and 1979. The sampling units used in the MIPS were: strata - Ottawa National Forest, Hiawatha National Forest, primary sampling unit (PSU) - forest compartment, secondary sampling unit (SSU) - a spruce-fir stand, and tertiary sampling unit (TSU) - circular plots (Mog et al. 1982, Mog 1981, Mog and Witter 1979). The PSU's and SSU's were weighted according to spruce-fir acreage and then selected at random for each national forest. Each SSU was divided into two approximately equal parts, and TSU's were randomly located within each half of the stand. A TSU was one of three circular plots of ca 0.05, 0.10 and 0.20 acres which were established around the plot center. Composite ground sampling unit refers to the three concentric circular plots nested around a single fixed plot center. The number of composite ground sampling units in the MIPS was 136 in 1979, but decreased slightly in succeeding years because a few of the sampled stands were harvested. The ground sampling units were measured each year from 1978 through 1984.

Results

Spruce budworm impact data for the years 1978 through 1983 is presented and discussed by national forest and selected districts for the following parameters: percent mortality, total dead volume, live basal area per acre, dead basal area per acre, and defoliation ranking. We chose three districts from each national forest to illustrate the variability of budworm impact within a national forest. Detailed impact information on the stands in the MIPS have been published (Lynch et al. 1982a-d, Mog et al. 1982).

Percent mortality. On a percent basis, approximately twice as much mortality occurred on balsam fir than on white or black spruce in the Hiawatha and Ottawa National Forests (Fig. 2).

Percent balsam fir mortality in the Hiawatha National Forest was extremely variable (Fig. 3). In the eastern districts, where the outbreak first started, balsam fir tree mortality was very high (e.g., 99% in the Sault Ste. Marie District, 74% in the St. Ignace District). The outbreak was present almost as long in the three western districts. However, average percent fir mortality was under 25% in each of the three western districts (Munising, Rapid River, and Manistique). The extreme differences in percent mortality between the eastern and western districts of the Hiawatha National Forest were probably due to the good markets for spruce and fir pulp in the western districts. There was little opportunity to

harvest fir timber in the eastern districts due to lack of markets.

Percent balsam fir mortality in the Ottawa National Forest ranged from 19 to 54% through 1983, with the highest mortality (30 to 54%) occurring in the most western and northern districts (Bessemer, Watersmeet, Ontonagon, Bergland) where the outbreak originated in the western Upper Peninsula. Average percent fir mortality increased considerably between 1980 and 1983 in the eastern districts of the Ottawa National Forest (Fig. 3). By 1983 fir mortality reached 19 and 30% in the Iron River and Kenton Districts, respectively.

Total dead volume. Balsam fir has suffered a much greater loss of growing stock volume than white or black spruce. In the Hiawatha and Ottawa National Forests, approximately 90 and 84% of the total fir volume died. Through 1983, the estimated total dead volume of balsam fir had reached over 17 and 20 million ft³ in the Hiawatha and Ottawa National Forests, respectively (Fig. 4). Total dead volume of balsam fir has tripled since 1978.

White spruce total dead volume showed a ten-fold and four-fold increase in the Hiawatha and Ottawa National Forests since 1978 (Fig. 4). Black spruce total dead volume doubled to tripled in both national forests during the last five years. At the end of 1983, total dead volume of white spruce was 1.4 and 2.4 million ft³ in the Hiawatha and Ottawa National Forests, respectively. The total dead volume of black spruce was 0.4 and 1.4 million ft³ in the Hiawatha and Ottawa National Forests, respectively. The relatively large volume of dead black spruce in the Ottawa National Forest may in part be attributed to site conditions and not completely due to budworm feeding (Mog et al. 1982).

Live and dead basal area. We present data for the amount of balsam fir basal area per acre only because the majority of live and dead basal area of susceptible host trees within the stands was balsam fir. A 36 and 30% reduction in live basal area of balsam fir was found in the Hiawatha and Ottawa National Forests, respectively, during the last five years (Fig. 5). A three- and four-fold increase in the amount of balsam fir dead basal area per acre has been observed since 1978. Estimated balsam fir dead basal area by 1983 for the Hiawatha National Forest was about 1.5 times that of the Ottawa National Forest. The balsam fir live basal area per acre remaining in 1983 was a little higher in the Hiawatha National Forest (27 ± 7 to 24 ± 3 ft²/ac).

Changes also have been noticed in the amount of total live basal area per acre of white and black spruce. The average annual change in the live volume of white spruce was -0.40 and 0.0 ft²/ac in the Hiawatha and Ottawa National Forests, respectively. The average annual change in the live volume of black spruce was +0.20 and 0.0 ft²/ac, in the Hiawatha and Ottawa National Forests, respectively.

Considerable variation in the amount of live and dead basal area of balsam fir has

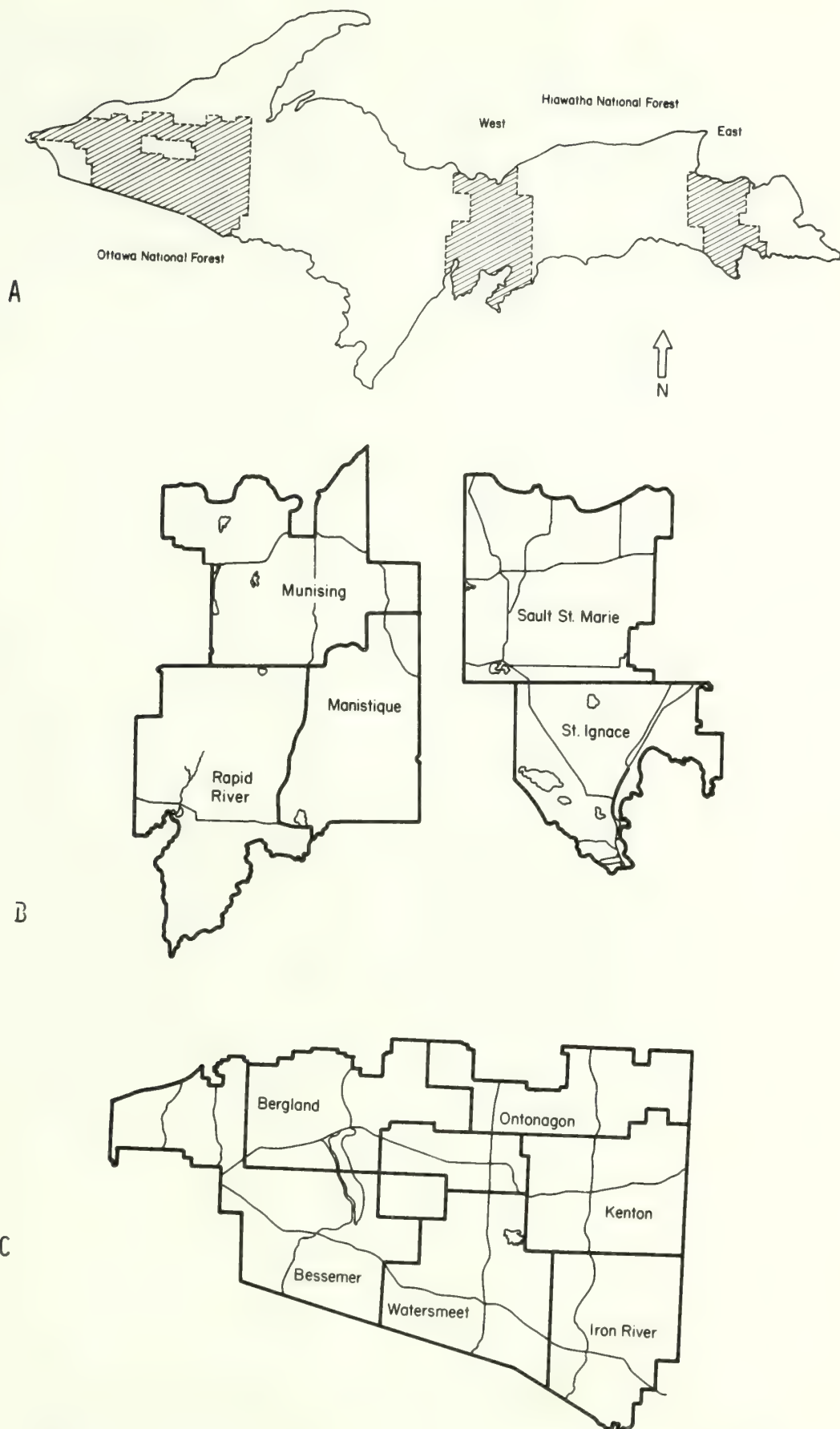


Fig. 1. Location of the: (A) Ottawa and Hiawatha National Forests, (B) districts in the Hiawatha National Forest, (C) districts in the Ottawa National Forest.

occurred in the various districts during the last five years (Fig. 6). In the Hiawatha National Forest, live balsam fir basal area/acre increased slightly in the Munising District, stayed about the same in the Manistique District, decreased about 20% in the Rapid River District, and decreased over 75% in the St. Ignace and Sault Ste. Marie Districts. Total dead balsam fir basal area/acre has increased three-fold in the Munising and Manistique Districts, but **still** was under 9 ft²/ac; increased ten-fold in the Rapid River District (equaled 20 ft²/ac in 1983); has reached over 40 ft²/ac in the St. Ignace and Sault Ste. Marie Districts.

In the Ottawa National Forest districts, live balsam fir basal area per acre has decreased 10 to 55% during the last five years. Total live balsam fir basal area varies from 14 ft²/ac in the Watersmeet District to 44 ft²/ac in the Kenton District. A two- to eight-fold increase in dead balsam fir basal area/ac has occurred in the western Upper Peninsula since 1978. By 1983, total dead balsam fir basal area/ac was 11 to 12 ft²/ac in the Bergland and Iron River Districts, 20 ft²/ac in the Bessemer District, and 25 ft²/ac in the Watersmeet, Ontonagon, and Kenton Districts.

Some of the factors responsible for these variations in the live and dead basal area of balsam fir are: (1) quantity of balsam fir present in stand prior to outbreak, (2) stand species composition, (3) site factors, particularly those indicative of soil moisture availability, and (4) length of time outbreak has been in progress (Lynch et al. 1984a).

Defoliation ranking. The average defoliation rankings for balsam fir, white spruce, and black spruce were similar in both national forests (Fig. 7). The defoliation ranking for balsam fir increased considerably between 1978 and 1980 and then stayed the same or decreased. There were small differences in the average defoliation ranking for white spruce and black spruce. The defoliation ranking by year for balsam fir was consistently higher than the corresponding defoliation ranking for spruce. For example, in 1980, the defoliation rank was 2.7 and 1.9 for balsam fir and spruce, respectively. This correlates with the pattern of greater mortality and growth loss exhibited by balsam fir over white and black spruce.

DISCUSSION

We briefly discuss the: (1) scientific and management implications of the MIPS, (2) number and size of plots within the MIPS, (3) variability within the MIPS, and (4) suggestions for reducing cost when sampling impact.

A thorough understanding of the interactions between the budworm, site conditions, and stands is necessary if we are going to manage the forest in an ecologically sound and financially rewarding manner. We have made considerable progress during the last seven years in developing a knowledge base (from the MIPS and other studies) on the spruce budworm

in the Lake States. Using the MIPS as the initial data base, short-term and long-term rating systems, which predict the amount of future damage to spruce-fir stands from budworm feeding, have been developed for the Lake States land manager (Olson et al. 1982, Lynch et al. 1984b). These systems provide land managers with additional decision-making tools (Witter and Lynch 1984). Further long-term studies on fir-budworm interactions (i.e., budworm-stand-site relationships, budworm population monitoring) are still necessary to improve our knowledge base and decision-making abilities.

Karpinski and Witter (1982) determined the number of plots (2-5) and plot size (0.05, 0.10, 0.20, 1.0 ac) required to quantify various impact parameters at a given allowable error. In general, the coefficient of variation decreased more rapidly by increasing the number of plots than by increasing plot size. The greatest reduction in the coefficient of variation occurred between 2 and 3 plots. We found that our sample scheme for the MIPS was adequate, but we recommend three 0.10 ac plots for future studies. Three 0.10 ac plots were used in our validation studies for the hazard-rating system.

It is difficult to make comprehensive statements concerning the percent allowable error of various parameters within the MIPS at the national forest, district, compartment, and stand levels. The coefficient of variation (percent allowable error) is generally much lower at the national forest level, sometimes quite variable at the district level, and usually reasonably good at the compartment or stand level. Lynch and Witter (1983a-d) compared the estimates for live trees (number/ac), percent tree mortality, live basal area, and dead basal area for additional plots sampled in each district in 1981 with the 1981 estimates from the MIPS. Comparisons were reasonably good for most estimates in districts with more MIPS plots, but some relatively large differences occurred in some districts with relatively few plots in the MIPS or where the MIPS sampled stands in that district may not have been very representative of the stands in that district. For example, tree mortality in the Sault Ste. Marie and St. Ignace Districts, based on the 1981 MIPS data was 99 and 71%, respectively. Supplementary data collected in 1981 indicated that fir mortality in these two districts may be only as high as 76 and 46%, respectively (Lynch and Witter 1983c).

Analysis of data from the MIPS indicated that the amount of variation within the data set was exceedingly large. For example, individual stands vary from little defoliation and no tree mortality to 100% fir mortality. We could have obtained more homogenous data within MIPS by: (1) sampling in just a few districts, (2) choosing only stands with a high percentage of fir, or (3) traveling the main roads and selecting stands within easy walking distance, thereby sampling relatively more stands with better drainage and fewer stands on very wet sites. Fowler and Witter (1982) reported that a

set of more homogenous stands, as just described, would probably yield less variable estimates than the estimates from the MIPS. However, the bias associated with such estimates of impact parameters for the entire spruce-fir forest could be very large. The accuracy of such estimates may be very low and the distortion of the probability statements due to bias very high. Therefore, estimates from the MIPS are probably not as precise as those based on a more homogenous set of stands. Nevertheless, they are more representative and more accurate with distinctly smaller biases. Fowler and Witter (1982) provide a detailed discussion on the accuracy and precision of impact parameters.

Hopefully, some of the extreme variation will be explained by current studies on the budworm-stand-site interactions. Intensive multiple-factor methods of site classification have been employed with success for over 50 years in Europe. Similar, but more extensive methods are widely used in Canada (Barnes et al. 1982). During 1982 and 1983, a classification system for spruce-fir stands was developed for the Ottawa National Forest. Twenty-one dryland and four wetland site units were distinguished on the basis of topographic features, soil factors of drainage and texture, and ground cover vegetation (Hix et al. 1983). Damage to balsam fir was proportionally greater by 10 to 25% on organic soils and on dryland ecosystems with somewhat poorly drained soils (Hix et al. 1984). The shallow rooting habit of balsam fir on these kinds of soils lowers the trees' ability to withstand defoliation and drought injury.

Collecting impact information is important, but very time consuming and expensive. We expect that more of the parameters required for measuring impact will be available from routine compartment inventories as forest management in the Lake States becomes more intensive. Also, a series of permanent plots which utilize pheromone traps for measuring budworm populations will be operational in Michigan's Upper Peninsula by 1985 or 1986. These changes in inventory methods for forest stands and pest populations may help considerably in reducing the cost of collecting impact data. We may further reduce the costs of gathering certain

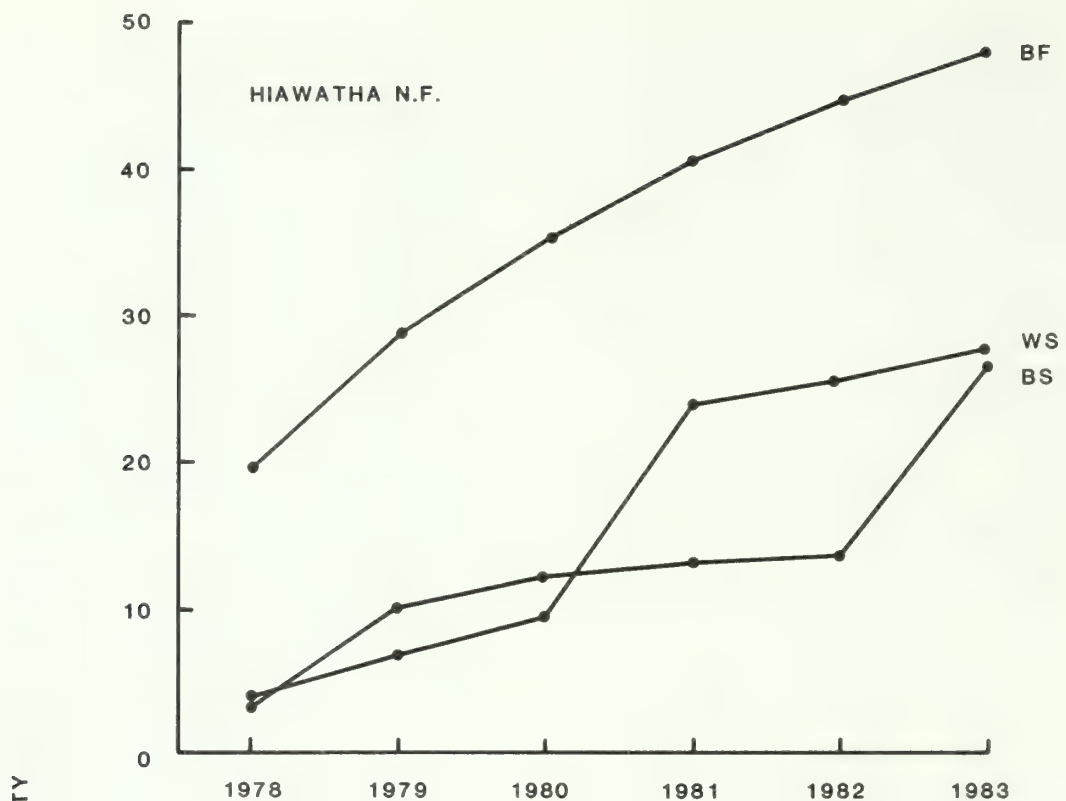
impact data by using data obtained from aerial photographs of permanent plots. Olson et al. (1982) and McCarthy et al. (1983) described the techniques that can be used to obtain impact data from 35 mm or 70 mm photography. Hopefully, comparable cost data of sampling impact from ground plot sampling and aerial photographs will be available shortly.

Technology Transfer

Technology transfer plans should precede research projects and then technology transfer actions should accompany each project (Allen et al. 1982). This helps ensure that the research is needed and that the results reach the user community in an appropriate and timely manner. Meetings with Lake States forest managers in 1977 and 1978 revealed a need for operational techniques to monitor spruce budworm damage. The Michigan Impact Plot System was established to assess budworm damage and to relate it to easily measured stand variables. Close contact was maintained between the land managers and the researchers. The University of Michigan and Michigan State University, with funding support from the CANUSA Program, became involved in 1981 in a technology transfer program for the Lake States Region (Montgomery et al. 1984b).

Needs-assessment surveys of forest managers and pest management specialists indicated that the technology transfer team should produce information packages on spruce budworm biology, insecticides, silviculture, remote sensing, and impact (Rogan et al. 1982a, b). A manual (Montgomery et al. 1983c), technical reports (Lynch et al. 1982a-d), handbooks (Flexner et al. 1983, Montgomery et al. 1982), leaflets (Lynch et al. 1984b, Montgomery et al. 1983a, b), and video tapes (Montgomery et al. 1984a) have been developed.

Specifically relating to the research work discussion under the MIPS, eight technical reports summarizing the amount of spruce budworm damage were distributed to the area's forest managers. News releases, popular articles, handbooks, and leaflets also were written to alert forest managers and landowners about the current status of the infestation and the use of short- and long-term rating systems.



% MORTALITY

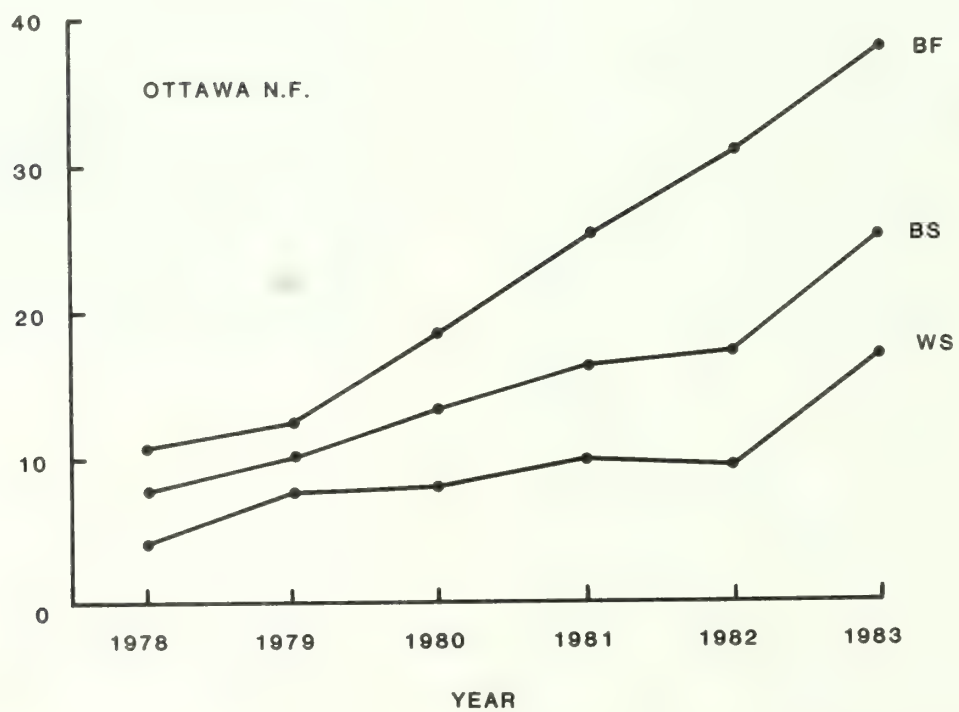


Fig. 2. Average percent mortality of balsam fir, white spruce, and black spruce on the two national forests, 1978-1983.

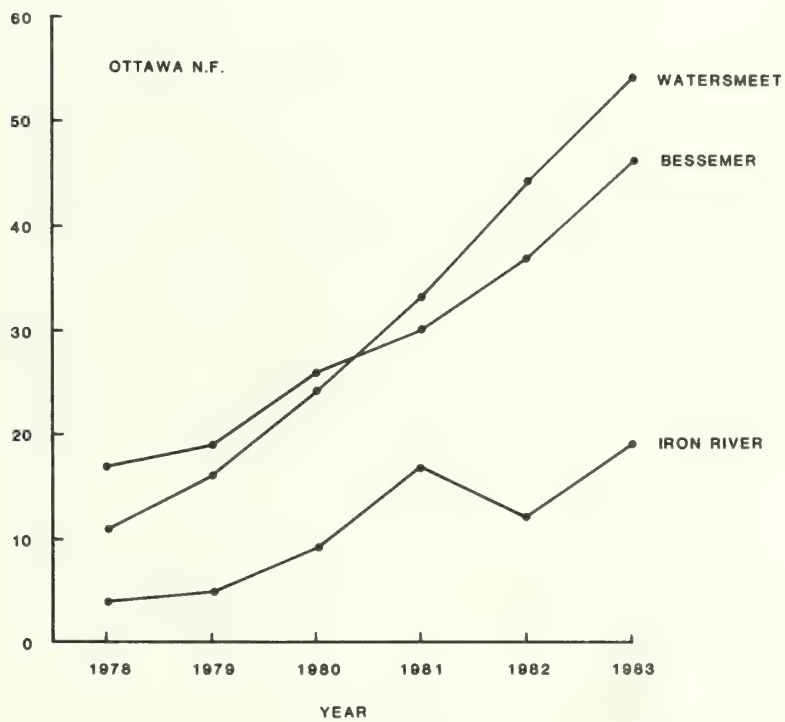
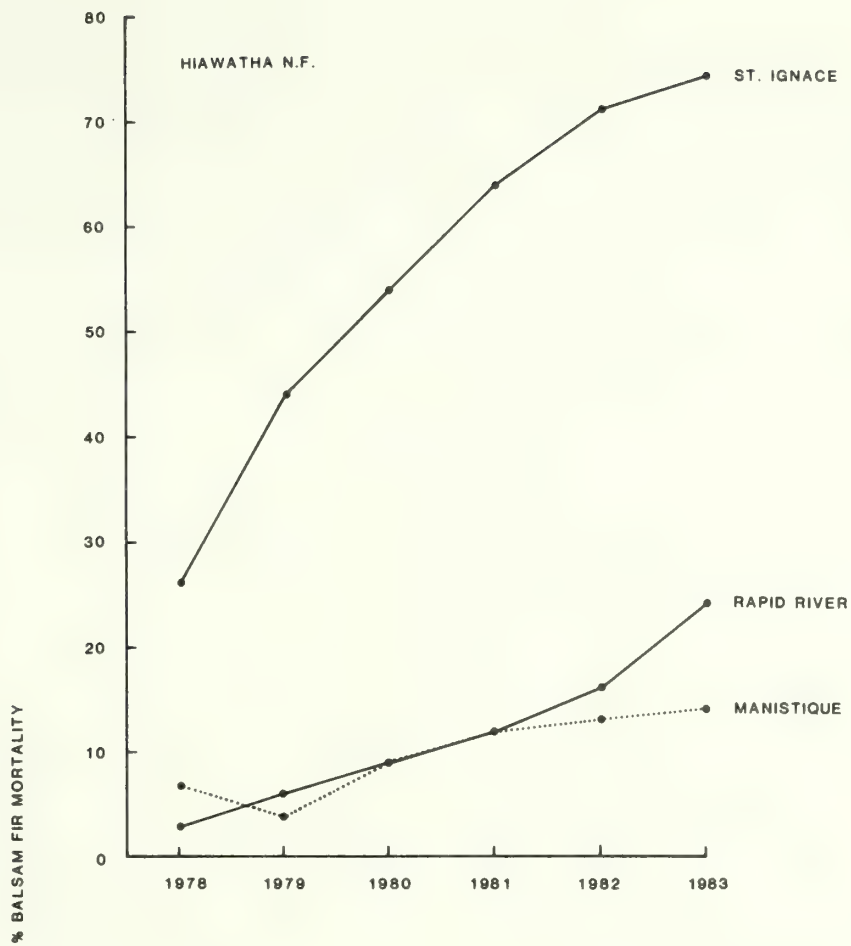


Fig. 3. Average percent mortality of balsam fir on selected districts in the two national forests, 1978-1983.

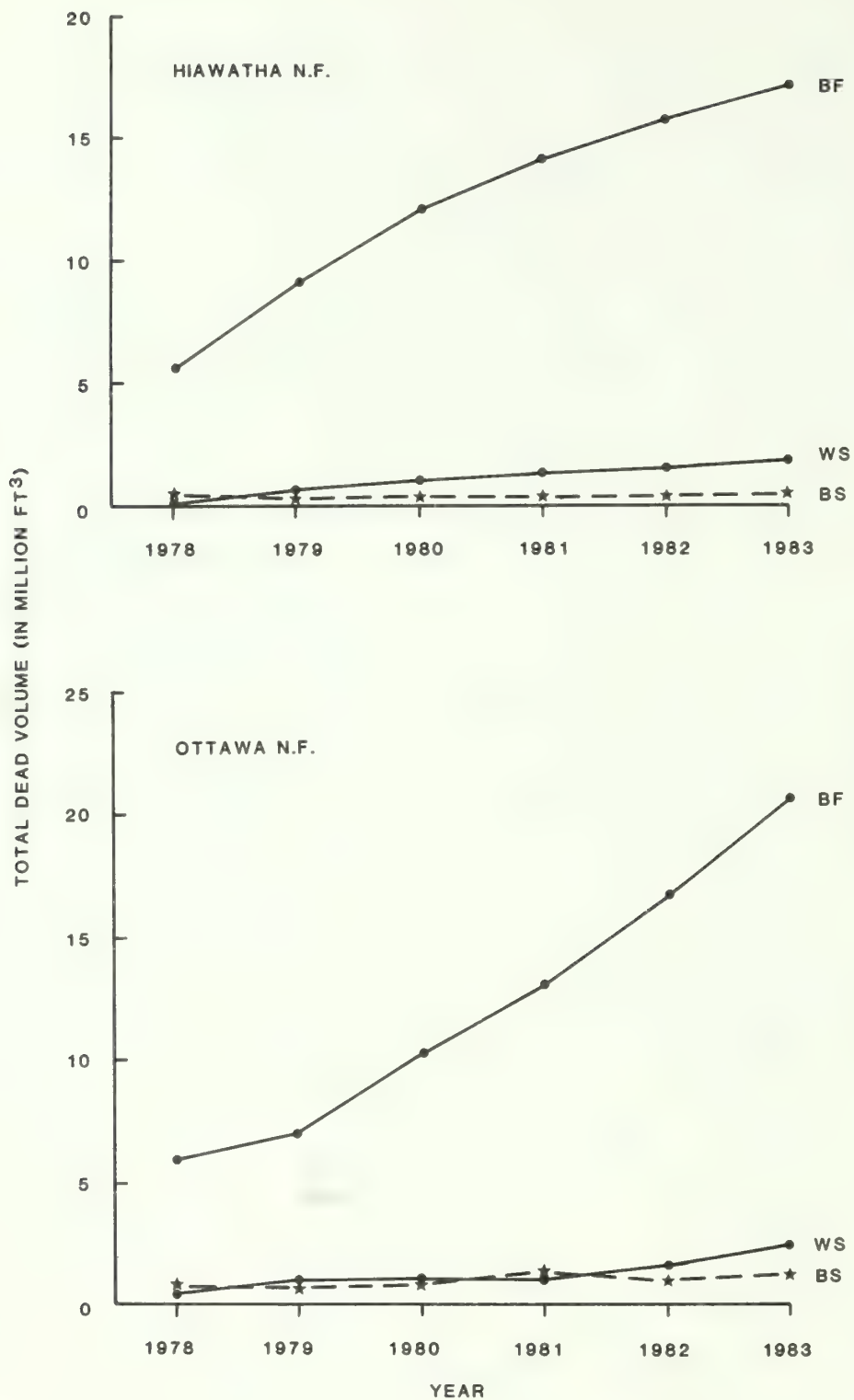


Fig. 4. Total dead volume (in million ft³) of balsam fir, white spruce, and black spruce on the two national forests, 1978-1983.

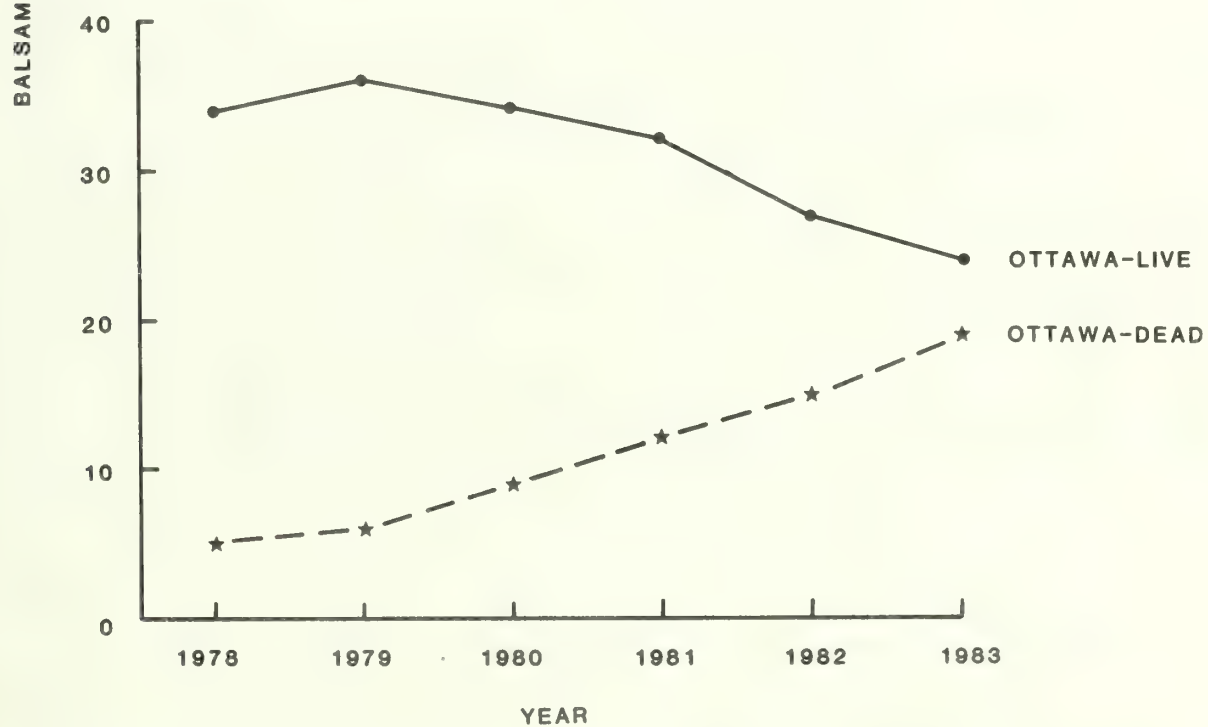
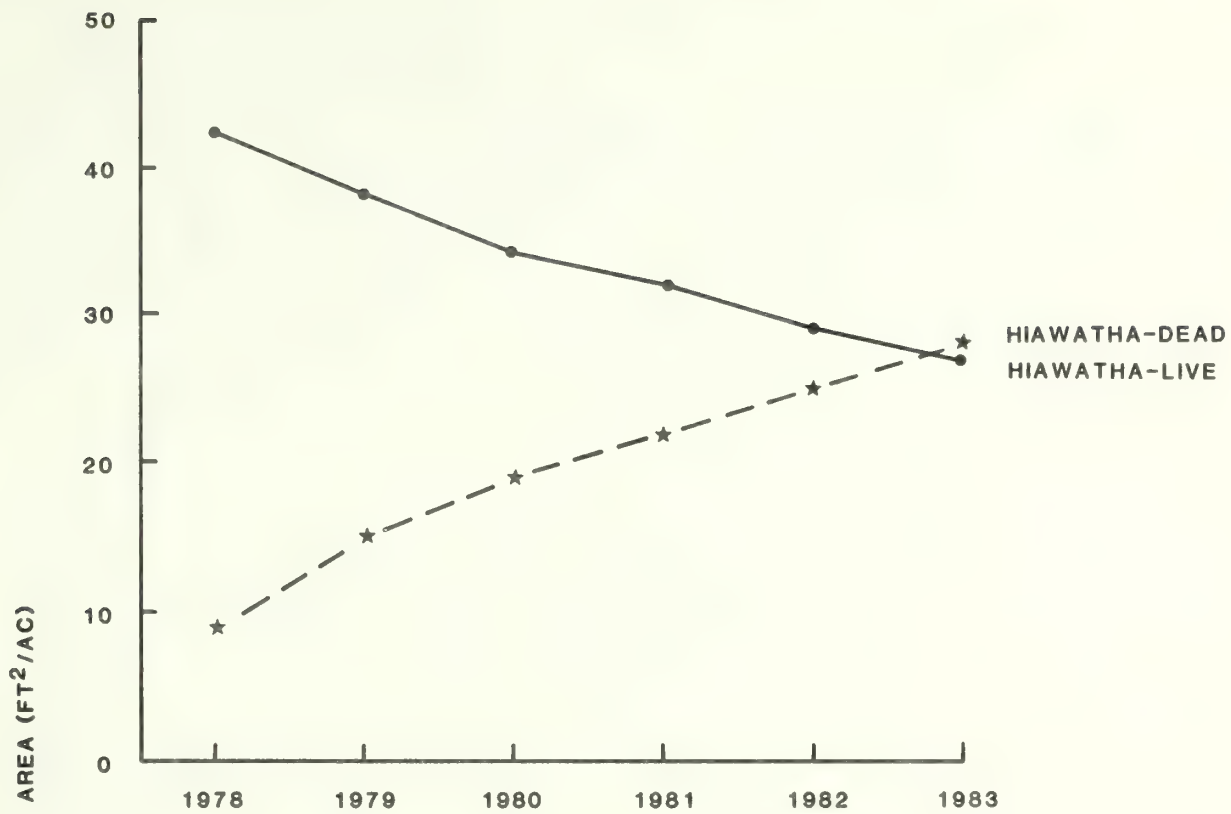


Fig. 5. Average dead and live basal area (ft²/ac) of balsam fir on the two national forests, 1978-1983.

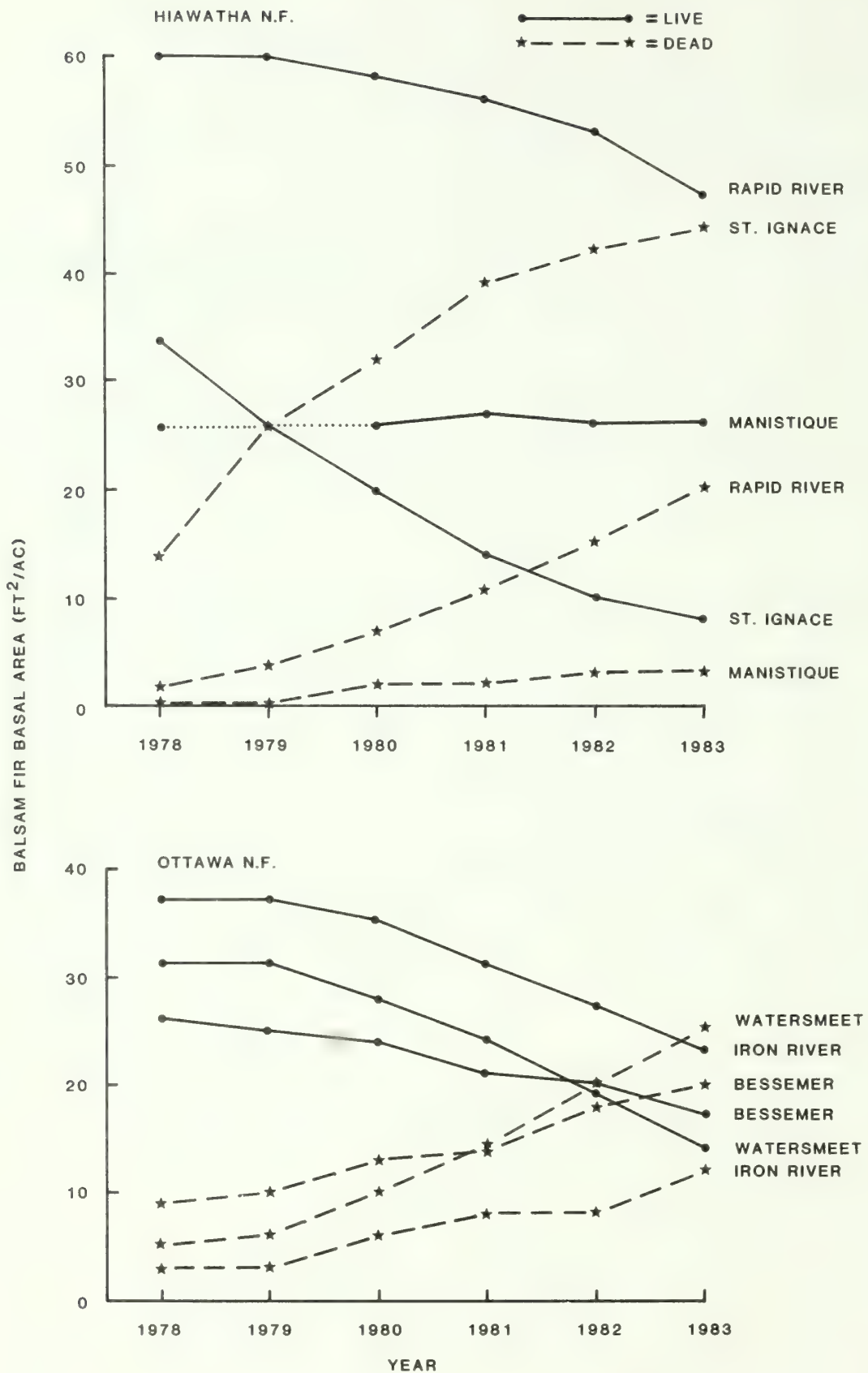


Fig. 6. Average dead and live basal area (ft²/ac) of balsam fir on selected districts in the two national forests, 1978-1983.

AVERAGE DEFOLIATION RANKING

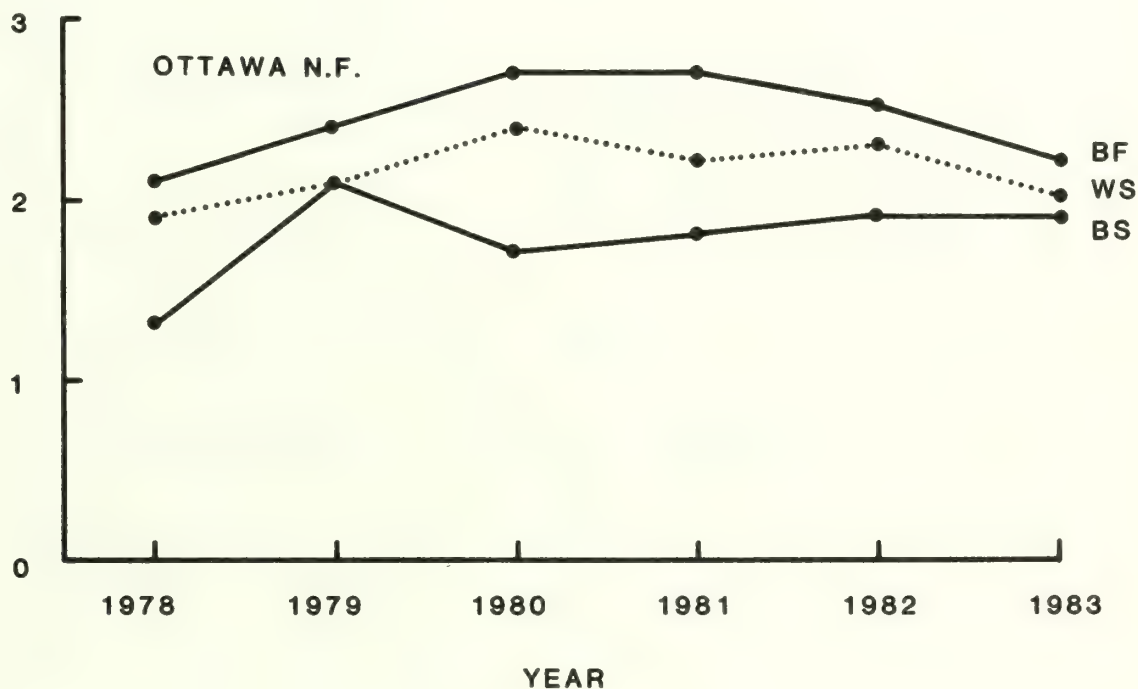
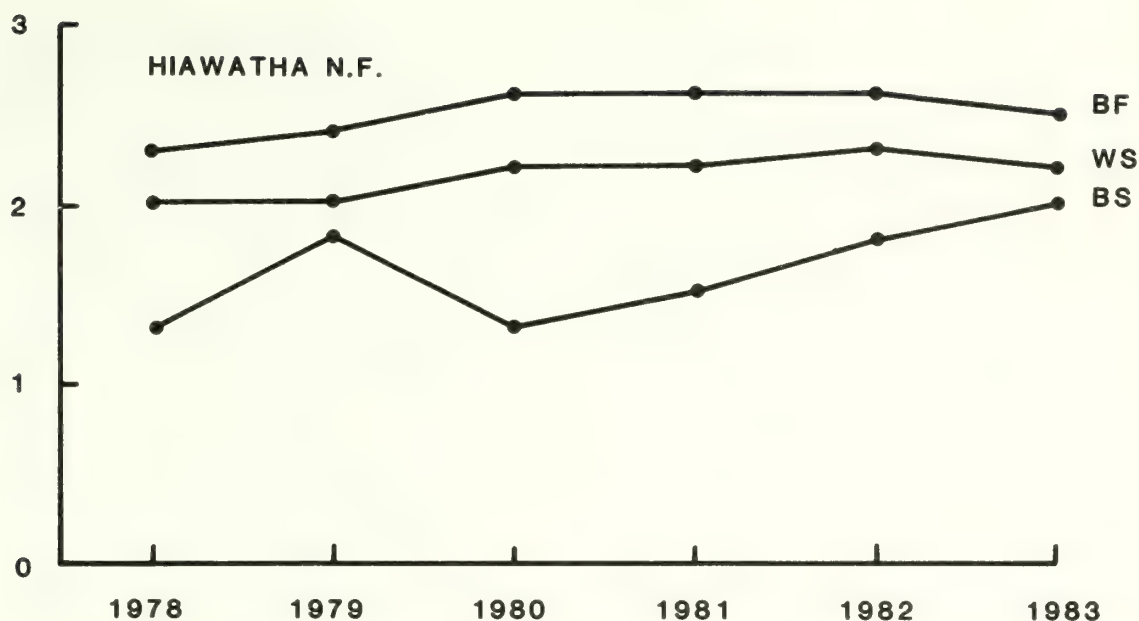


Fig. 7. Average defoliation ranking of balsam fir, white spruce, and black spruce on the two national forests, 1978-1983. Defoliation ranking: (1) no defoliation - no observable feeding damage, 0 to 20% of total foliage missing; (2) light to moderate defoliation - 21 to 50% of total foliage; (3) heavy defoliation - 51% or greater defoliation with no observable top-kill; and (4) severe defoliation - 51% or greater defoliation with obvious top-kill.

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SPRUCE BUDWORM IN MINNESOTA: LOSS ASSESSMENT CURRENT CONDITIONS AND MANAGEMENT OPTIONS

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ABSTRACT: The spruce-fir coevertype is the dominant forest type in Northeastern Minnesota and today consists of approximately 930,800 acres of commercial forest land. The resource is present as pure stands of varying quality that typically consist of 80% balsam and 20% white spruce. Additional spruce-fir occurs in mixedwood stands as part of the lowland black spruce and hardwood types or as clumps amidst upland aspen and other conifers. Budworm outbreaks have been reported at periodic intervals from 1825 to the present, but populations can always be found somewhere in the northeastern sections of the state. Direct control projects ceased in 1976. Noticeable defoliation in 1983 was limited to 138,700 acres in St. Louis, Lake and Cook counties. Loss assessment projects have been conducted in Minnesota from 1940 to 1982. Stand conditions today reflect the damage of past outbreaks, low management intensity and historic underutilization of the balsam resource. Foresters recognize the continuing threat of spruce budworm damage in Northeastern Minnesota and management targets include: conversion to aspen, red pine or white spruce where possible and increasing the spruce component of remaining stands. As markets allow, harvest is followed by site preparation and the planting of bare root stock. Rotations of 40 to 50 years are being pursued on all sites. High site index stands may be managed for future bolt markets.

Introduction

The spruce-fir coevertype in Minnesota (MN) today consists of approximately 930,800 acres of commercial forest land primarily in the northeastern quarter of the state. Additional spruce-fir resources are contained here in stands of mixed species (mixedwood) typed as aspen, birch, cedar and lowland hardwoods and black spruce. Solid spruce-fir stands contain about 20% white spruce, while the mixedwood stands contain spruce-fir clumps with various combinations of aspen, birch, red maple, ash, cedar and pine. The solid spruce-fir stands often contain advance balsam reproduction. In mixedwood stands the understory is hardwoods, brush or balsam depending on seed source. Ownership patterns vary, but large blocks of county, state, federal and industrial land are broken up by scattered small private ownerships of high recreational value often centered around water resources.

Budworm outbreaks have been reported in the state from 1825 to the present. The amount and location of budworm defoliation in Northern Minnesota is surveyed and reported annually by the

Minnesota Division of Forestry. Erickson and Hastings (1978) reported this information from 1954 to 1977. Aerial spray programs using a variety of chemicals were conducted on both industrial and public land in the state from 1958 to 1976, to either protect foliage in recreational areas or sustain timber stands until they could be harvested.

Minnesota currently contains an abundance of budworm susceptible stands due to past outbreaks, limited markets and harvest (cutting) procedures. Budworm activity has left a backlog of stands needing salvage or treatment. Aspen is a desirable product for the high quality paper mills and chipboard plants of Minnesota. Spruce has retained a stagnant market in the procurement for the predominantly groundwood paper mills. Balsam fir, however, has had only a limited market, and in many portions of the state it is considered non-marketable if part of a mixedwood stand. In the past, when harvesting removed only the aspen and spruce, development money was not always available to treat the balsam residual. Until recently, intensified management has been limited to select industrial lands.

Loss Assessment

Numerous projects have been undertaken in Minnesota to monitor spruce-fir mortality and growth loss during budworm epidemics. This paper will review seven studies that have had an impact on forest management in the state.

Graham and Orr (1940) began the process by reporting on the 1912-1923 budworm outbreak. The majority of the report consists of budworm bionomics and is still very useful today. It also contained the first loss assessment information available to foresters in the state. They reported using a "large number" of one-tenth acre sample plots in the solid spruce stands of Northern Minnesota to estimate that 85-90% of the merchantable balsam fir in the area, nearly 20 million cords, was lost. They noted that injury to spruce varied so much from place to place that they couldn't estimate volume losses.

Industry in Minnesota has conducted several assessments of the real and potential dollar losses due to budworm outbreaks. The Kimberly-Clark Corporation¹ recognized that the amount of susceptible balsam was increasing on their lands due to several factors: the early emphasis on logging white pine and later white spruce, black spruce and birch; fire exclusion and preferential harvesting of aspen and jack pine. In a series of studies from 1951 to 1956 they used standard inventory procedures to assess the extent of their susceptible

¹/Kimberly-Clark of Minnesota. 1956. Internal documents. Balsam fir decay and cull on different sites, with rotation age recommendations. 10 pp. Spruce budworm problems in Minnesota. 18 pp.

holdings. In addition, they documented that top kill from budworm feeding was more important in timber loss than butt rots. They concluded the next budworm outbreak in Northeastern Minnesota would produce a surplus of salvage wood and decided it would be better to harvest mature stands of clean sound pulpwood on a priority basis and leave the overmature, inaccessible stands to regenerate themselves and produce wood for the next rotation. Boise Cascade (1970)² later concluded in assessing their holdings that a projected kill of 250,000 cords of balsam would result in a loss of 750,000 to one million dollars. They determined that the loss of this balsam component of their stands would make it too costly to cut the remaining timber when considering the cost of road construction and taxes. Boise Cascade was a strong supporter of direct control operations in Minnesota.

In 1972 the U.S. Forest Service, industry and the MN Forest Pest Management Group cooperated to conduct a survey to determine the amount of tree mortality caused by the budworm on the central portion of the Kabetogoma Peninsula. This survey related defoliation class as determined by aerial survey to three tree condition classes: live, dead and topkill. The ground survey consisted of clusters of 4 tenth acre plots on 47 randomly selected plot centers within the affected spruce-fir acreages. This was the first detailed study that combined aerial damage detection with population monitoring, stand composition and tree loss data. Unfortunately, it was a one year project and its potential value was apparently lost in the days when the major management effort was to utilize direct control operations in an effort to store risk timber on the stump. Batzer (1973), however, began to look at the long range impact of outbreaks. He documented that mortality or growth reduction occurred until four to five years after an outbreak began and that 60% of the loss to balsam fir growing stock actually occurred during the five years after an outbreak subsided. He suggested that decisions concerning suppression should be made during the first three years of an infestation.

The state Division of Forestry conducted a management inventory (called Phase II) of the 105,000 acre Finland State Forest in Lake and Cook counties from 1978 to 1980. This survey period was after a budworm epidemic that resulted in direct control operations in 1974 and widespread budworm caused mortality into 1976. Stands severely defoliated from 1972 on were still marketable until 1976, when drought wiped out the remaining stressed balsam. This produced a surplus of stands needing harvest that local markets could not handle. Regulation schemes were thoroughly disrupted and field survey could not keep up with the continuing mortality. At that time, management was reduced to salvage where possible and limited development work based on site index priority. The inventory project was conducted

to reestablish a management base. The field survey gathered information on coverytype acres, species composition, size class, basal area, understory composition, site index, mortality and active pest agents. Crews made on site decisions as to when the stand should be harvested. Stands were coded as high risk when active pest agents and current mortality justified harvest within one to five years. Computer systems then generated coverytype maps and numerous stand tables and graphics for the foresters use in planning allowable cuts, overall coverytype targets and development work. Detailed pest management printouts included a listing of all balsam fir coverytypes with high risk by age, site index and location; a list of additional coverytypes with balsam fir mortality by coverytype, age and location; and a total of the acreages of all coverytypes with balsam fir mortality. Printouts indicated that of 68,692 acres of commercial forest, 13,806 acres of various coverytypes contained dead balsam fir that needed harvest within the next five years. The alterations procedure that is inherent in Minnesotas' Phase II inventory system follows timber sale closure, declaration of a lost type and mandatory regeneration checks for both artificial and natural restocking. Alterations are still documenting the combined impact of budworm and drought in the Finland State Forest.

Campbell and Albers (1983)³ cooperated with State and Private Forestry of the U.S. Forest Service to record the location and intensity of budworm defoliation in 1982 and to estimate the volume of spruce and fir lost due to budworm from 1977 to 1982 in Northeastern Minnesota. During this period the only mortality in Minnesota occurred in an 84 township area of St. Louis and Lake counties. Sketch mappers identified stands in this new outbreak area that contained at least 25% balsam fir and/or white spruce. These areas were then categorized by percent mortality into three classes: 1-19% dead host trees, 20-49% dead and 50-100% dead. From the sketch mapping, the acreage of each stand was established and ground survey procedures using a 10 BAF prism were conducted to determine the number of live, risk and dead balsam fir, white and black spruce within plot boundaries. From the data they computed average volume loss per acre for each of the three mortality categories, overall loss per acre, basal area of host trees and the percent of dead and risk host trees on each sample plot. The study documented that 493,829 cords of balsam fir and 8,036 cords of white spruce were lost during the five year period. This represented 20% of the available volume of balsam fir in the affected area. Black spruce losses were not detected during the ground survey and white spruce losses were negligible. Valuable experience was gained for integrating aerial survey with ground loss assessment in Minnesota's mixedwood stands. Future loss assessments

²/Boise Cascade. 1970. Woodlands division report.

³/Campbell, J., and M. Albers. 1983. Final Report. Spruce budworm: mortality loss assessment in Minnesota, 1977-1982. Mn. DNR - Forestry report to U.S.F.S. - S.P.F. St. Paul, MN, 20 pp.

will only use two mortality categories, greater or less than 50% dead, and the number of prism plots will be increased in each survey area and established along a transect to increase accuracy in stands where the spruce-fir distribution is discontinuous.

Current Conditions

Noticeable spruce budworm defoliation is currently restricted to approximately 138,700 acres of the spruce-fir type in St. Louis, Lake and Cook counties. Other low intensity budworm populations have been detected to the south and west of these areas in mixedwood forests. These stands are monitored annually to detect buildup and spread potential.

Campbell and Albers (1983) estimated that budworm caused mortality occurred on 185,878 acres at the rate of 0.5 cords/acre/year from 1977 to 1982. However, they also report that in Lake and St. Louis counties the allowable cut for balsam fir from 1977-1982 totalled 891,000 cords and only 25% of this sold. This reflects current markets that are depressed due to reliance instate on aspen, jackpine and spruce for the majority of pulp, the high trucking costs to outstate mills and the current Canadian overcutting and monetary discount that makes it cheaper to buy Canadian Kraft than cut and process Minnesota wood. Logging operability continues to be a problem on remote, wet, rocky, or steep sites. Some of these stands are currently left to regenerate untouched.

The question again being asked in Minnesota, is whether the justification exists to undertake budworm related management when the current demand for the resource from public land is inadequate to deal with the backlog of overmature and damaged stands created by poor markets and past outbreaks. Currently, direct control would only be considered for high value recreational stands and microbials would receive first priority. Because balsam-fir and birch from mixedwood stands are non-marketable in some areas of the state, a new governor's task force is mandated to develop ways to handle this residual problem. While new political and management trends may develop, the ground level managers response to a spruce budworm outbreak in his district will continue to be mandated by local stand conditions, markets and available development money.

Management Outlook

Minnesota foresters continue to deal with the spruce budworm on a stand management basis. Essentially two types of solid spruce-fir stands and a third mixedwood type exists in Minnesota.

Operable stands with a good or better site index (greater than 52) are typically on clay soils and possess trees of good form. They are managed on a 50 year rotation. Such sites would be targeted for bolt production if the dimension lumber market expands in Minnesota along the grade

specifications established by Sinclair, Garrett and Bowyer (1981). Currently these stands are usually harvested for pulp. Many sites harvested in this manner do not receive additional site preparation before planting. On sites where there is partial or no harvest, rock raking is used to level and/or pile the residual and expose mineral soil before planting bare root stock. Direct seeding has not produced desirable stocking levels. In areas of historic budworm outbreaks, white spruce or red pine seedlings have been planted on the appropriate soils. Red pine was planted in pure blocks or mixed with white spruce to break up large spruce-fir stands. White spruce planting was considered successful if 300 stems of white spruce per acre persisted with various amounts of volunteer balsam fir. At 40 or 50 years the forester will have two options: remove the balsam and hold the spruce for sawlogs or clearcut the entire stand.

Additional spruce-fir stands are typified by site indexes of 41 or less with some combination of shallow soils, poor logging terrain and trees of squat form with numerous persistent branches. Operability of the sites will remain low, but if pulp markets strengthen they will be clearcut at 40 to 50 years and planted to spruce. Larch may be a future option.

Operability of mixedwood stands also depends on site factors, but the additional work of sorting mixed products makes them less desirable to loggers. Although attempts have been made to sell the spruce-fir clumps in a stand first and then followup with a winter hardwood clearcut, on most sites residual dense hardwoods and fir need post sale treatment. Rock raking into windrows, roller chopping and chaining and burning have all been attempted with follow-up planting to red pine, jack pine or white spruce. Where possible, clearcuts are enforced to convert to aspen if its site index is 60 or greater.

On a larger scale, ten year regulation schemes are being developed for state forest management units in the northeast. Spruce-fir stands are stratified by site index and targeted for harvest, potential conversion or follow-up development work such as fire, interplanting and release. Extensive planting of white spruce and/or red pine must be avoided due to yellowheaded spruce sawfly *Pikonema alaskensis* (Rohwer), the North America strain of *Scleroderma gremmeniella abietina* (Lagerb.) and other pests in the state. Regulation schemes will have to be continually updated in relation to current pest populations, mortality predictions and the cyclic availability of development money. Markets will remain a problem, and increased utilization of balsam bolts would compound budworm problems if rotations of greater than 50 years were attempted.

The recognized need to promote species diversity and regulate basal area and age structure in historic outbreak areas is accelerating the move from custodial to active management on state, county and industrial land. Campbell and Albers (1983) point out, however, that unmanaged stands

in the Boundary Waters Canoe Area and Voyageurs National Park may serve as sources of spruce budworm populations for Northeastern Minnesota. The effectiveness of silvicultural recommendations would be reduced if outbreaks spread from the unmanaged BWCA and Voyageurs National Park stands.

If short and long term market commitments for Minnesota woodsheds can be established, foresters would have the ability to regulate spruce budworm impact by integrating site specific inventory data with pest management projections. Ten year regulation schemes could be used to break up susceptible types and remove high risk stands in response to annual budworm population and damage surveys, and mortality predictions based on previous loss assessment projects.

Campbell and Albers (1983) presented the past and future of Northeastern Minnesota budworm conditions. "From the initial outbreak area near International Falls and Ely, budworm populations have spread through balsam fir stands to the south and east during the last 30 years. As the outbreak reached the southern edge of the extensive balsam fir type, young stands in the northern part of the State were maturing and again becoming favorable as host trees. Previously unaffected balsam fir growing in old kill areas have been and are becoming reinfested. Minnesota outbreaks do not occur with long periods of subsidence. Northeastern Minnesota has experienced a continuous infestation for the past 30 years and this situation is likely to continue." If markets do not solidify, foresters will be unable to harvest or treat susceptible stands and the loss cycle will continue.

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Abstract.--Three statewide inventories (1959, 1971, and 1982) show trends in area, number of trees, and volume of the spruce-fir resource. In general, there are more sawtimber stands, overstocked stands, and sawtimber volume; fewer pole-sized trees; and less growing-stock volume. Relatively high mortality and removals levels have contributed toward the overall decline of the resource.

Introduction

The Forest Inventory and Analysis Unit (FIA) of the Northeastern Forest Experiment Station, USDA Forest Service, has conducted three statewide forest inventories of Maine: 1959 (Ferguson and Longwood 1960), 1971 (Ferguson and Kingsley 1972), and 1982¹. In each of these surveys we collected data on the spruce-fir resource, and we are now in a position to analyze some of the important characteristics and trends in this dominant component of Maine's forest land. The data were collected by geographic sampling unit (Fig. 1).

There are several ways to look at this resource. The one that is most relevant in terms of area analyses is the spruce-fir forest-type group. Number of trees is useful in looking at the individual species for tree and diameter-class distribution, as well as defoliation class. Various volume estimates of the fir and spruce species are helpful from the commodity perspective. Components of the change in volume will give some clues as to why and how the species are changing.

The timing of the three surveys also allows us to analyze the impact of spruce budworm. Between the first and second inventories there was little budworm activity, while between the second and third inventories there was relatively heavy budworm impact. So, comparing the 1971 data with the 1982 data may help us to see effects of this pest. At the same time, however, we must remember that the resource is complex and dynamic. Budworm is only one of several factors controlling the change of Maine's spruce-fir forests. Age distribution, overstocking, and man's impact are also important and often cannot

¹Powell, Douglas S.; Dickson, David R. Forest statistics for Maine: 1971 and 1982. Resour. Bull. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. (In publication process).

be isolated. This complexity calls for careful and discriminating interpretation.



Figure 1.--Except for the three units in southwestern Maine, each county is a geographic sampling unit.

The Spruce-fir Forest-type Group

The spruce-fir forest-type group is a combination of several forest types that share closely associated species or site requirements. The group is used to classify timberland in which red spruce, northern white-cedar, balsam fir, white spruce, black spruce, or tamarack, singly or in combination, comprise a plurality of the basal area stocking of all live trees. In 1982 the area of this type group was 7.8 million acres, or 46 percent of the state's timberland base. The area declined 7 percent since 1971. However, the state showed no decline in timberland, and this means that the acreage lost by spruce-fir was picked up by other forest types.

Stand-size class is a classification based on the size of trees growing in an area. The area of spruce-fir is composed of 4.1 million acres of sawtimber stands (53 percent), 2.9 million acres of poletimber stands (37 percent), and 800,000 acres of sapling-seedling and nonstocked areas (10 percent). This distribution is more weighted toward sawtimber stands than is the state average (50 percent) of all forest types. And even though the area of spruce-fir has declined since 1971, the area of spruce-fir sawtimber stands has increased. The other two classes have declined.

Timberland is also classified by the amount of live-tree biomass per acre--green ton stand-volume class. Spruce-fir stands ranged from 0 to more than 200 tons per acre in 1982. The distribution was somewhat bell-shaped, though its peak was relatively flat between 50 and 125 tons per acre. The 1971 distribution was nearly identical except that there were more stands in the 50-to 125-tons-per-acre classes, with a definite peak in the 75-to 100-ton class. This increase represents the stand-volume classes that moved from spruce-fir into other forest types.

The consensus is that the spruce-fir resource is overstocked. Our surveys support this and show a decided shift in this direction (Fig. 2). If we ignore dead and unmerchantable trees and focus on growing-stock trees, the spruce-fir resource is anything but understocked. In 1971, 79 percent of the stands were full to overstocked and by 1982 this figure was 82 percent. Even more startling is the shift that occurred within the fully stocked and the overstocked classes. In 1971 the area in these classes was relatively even, 41 and 38 percent, respectively. By 1982 these proportions were 21 and 60 percent, respectively. The area in overstocked stands went up dramatically.

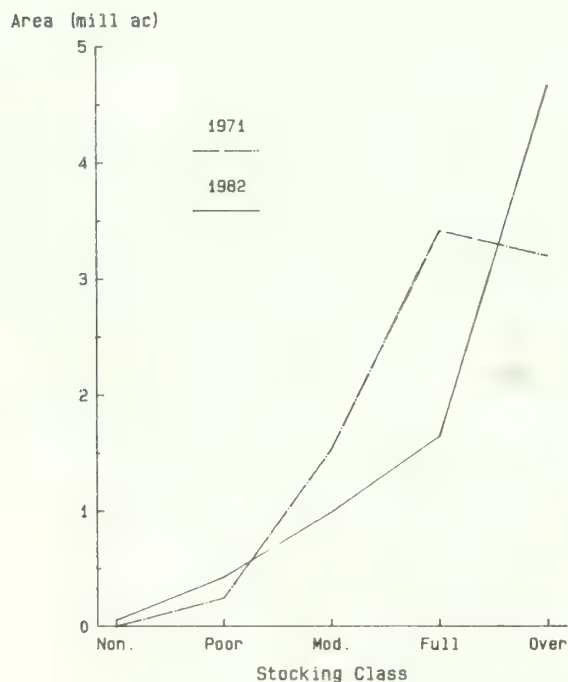


Figure 2.--Spruce-fir area by growing-stock stocking class, Maine, 1971 and 1982.

Keep in mind that stocking is a measure of occupancy of a site and need not be correlated to volume. It is quite possible to have an overstocked stand of fir seedlings with no volume at all. So, what accounts for this big increase in overstocked stands? It can happen in undisturbed stands by increases in number and size of stems. But more common in spruce-fir stands is an increase in the number of seedlings on stands where the overstory has been disturbed by harvesting or spruce budworm attack. Spraying, as a budworm control and tree protection measure, may also have allowed stocking levels to build.

The growing-stock volume of the spruce-fir forest-type group in 1982 was 11.8 billion cubic feet. This was 52 percent of the total volume in the state. Since this type group had only 46 percent of the area, this means that spruce-fir contains more volume on the average than other forest types. This group contains almost 80 percent of the spruce and fir volume in Maine. While this group is composed of many species, spruce and fir together account for two-thirds of the volume. In 1971, spruce and fir accounted for 72 percent of the group's volume. The major species are balsam fir and red spruce. In 1971, fir was number one with 35 percent of the group's volume, and red spruce was number two with 31 percent. In 1982, the roles were reversed with red spruce on top: 32 to 26 percent.

These statistics indicate two things. One, that spruce and fir within the spruce-fir forest-type group are less dominant than before. The resource is being diluted, and this supports the hypothesis that spruce-fir is declining in acreage not due to change in land use patterns, but rather to shifts in species composition. And two, the fir resource within the group is declining, and red spruce is holding its own to assume the lead role.

Number of Trees

Turning from a focus on area dominated by spruce and fir, we look at the species themselves as they are found throughout the state--first by studying numbers of trees and later by dealing with volume.

Tree class is used to group trees by their potential for producing high-quality lumber. Growing-stock trees are divided into two classes: preferred trees or those that are of highest quality, and acceptable trees that are merchantable but not good enough to be preferred. Trees that are alive but unmerchantable due to rot or poor form are cull. And a fourth category is dead trees that includes trees that have recently died and are salvable, and dead trees that are still standing but are no longer of any possible use for lumber.

Figure 3 shows the tree-class distributions for our species of interest. All species in Maine averaged 73 percent in the two growing-stock classes (20 percent preferred and 53 percent acceptable). Balsam fir had 68 percent growing stock (21 percent preferred, and 47 percent acceptable). Thus, fir has a less favorable breakdown, especially in the acceptable class. The spruce species, on the other hand, had 88 percent in growing stock--35 percent in preferred and 53 percent in acceptable. From a lumber viewpoint, the spruce resource looks very good. Averaging spruce and fir yields a 77 percent share of growing stock--still above average thanks to spruce.

The cull-tree class is also interesting. The average for all species was 16 percent. Balsam fir, often known as a tree prone to decay as it matures in crowded stands, had a surprisingly low 11 percent cull. But spruce was even better with a mere 6 percent of its trees classed as cull. So, the spruce and fir resource as a whole is in better condition, in terms of cull, than are the other species in Maine.

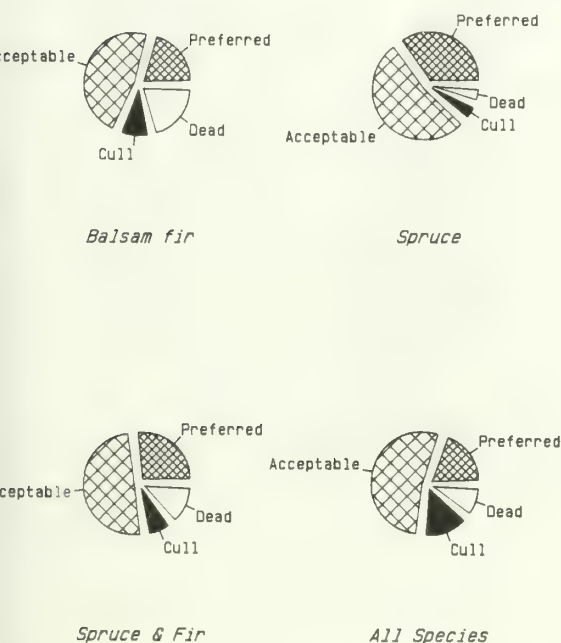


Figure 3.--Tree-class distributions for balsam fir, spruce, spruce and fir, and all species in Maine, 1982. Note: preferred plus acceptable equals growing stock.

Since the spruce budworm kills trees, the dead category may be most pertinent at present. As shown in figure 3, the fir resource is hurting, with 21 out of 100 trees dead. This is nearly double the 11 percent for all species. Spruce is in much better shape with only 6 percent of its trees dead. While all of this mortality is not attributable to budworm, there is no question that balsam fir has borne the brunt of the attack through the latest inventory. Since then there have been reports of increased spruce mortality, so these relationships may be somewhat different today. Our next survey should verify this more recent spruce decline.

Analyzing numbers of trees across diameter classes gives us a perception of the relative size of the species. In figure 4 the percent of all live trees for all species has been calculated for fir and spruce and plotted over diameter class. This not only shows the size relationship of fir and spruce, but also how important these species are to the entire forest resource of Maine. For instance, if you consider all live seedlings of all species in the state, 26 out of 100 of them will be balsam fir! Spruce only contributes about 7 percent to this class. At the 8-inch class, where the two lines intersect, spruce and fir together account for 45 percent of all live trees in Maine.

Figure 4 shows some real difference between spruce and fir. Except for an increase between the first and second class, fir shows a steadily decreasing trend as diameter increases. Its dominant role is played in the smaller size classes. The spruce species show more of a broad, bell-shaped trend. For trees between 5 and 15 inches in diameter, the spruce curve is relatively constant at around 21 percent. So in the spruce-fir resource, fir's niche is in trees smaller than 8 inches in diameter while spruce's niche is in large poletimber- and sawtimber-size trees.

In an effort to assess more directly the impact of spruce budworm on this resource, FIA collected data on the extent of defoliation of the crown of growing-stock trees. No attempt was made to distinguish between current and previous years' foliage, but the crown as a whole was observed from a distance and put into one of our classes: no defoliation, 1 to 30 percent defoliated, 31 to 69 percent defoliated, and 70 to 100 percent defoliated. This procedure is an evaluation of the vitality of the tree and should not be confused with the more standard defoliation surveys, which involve close examination of tree branches. (These intensive surveys have shown higher levels of defoliation, especially in the lighter categories. Personal communication, Thomas Rumpf, Maine Forest Service.) Figure 5 shows the FIA defoliation classes for the three spruce species and balsam fir. In order of increasing levels of some degree of defoliation, the species are black spruce (18 percent), red

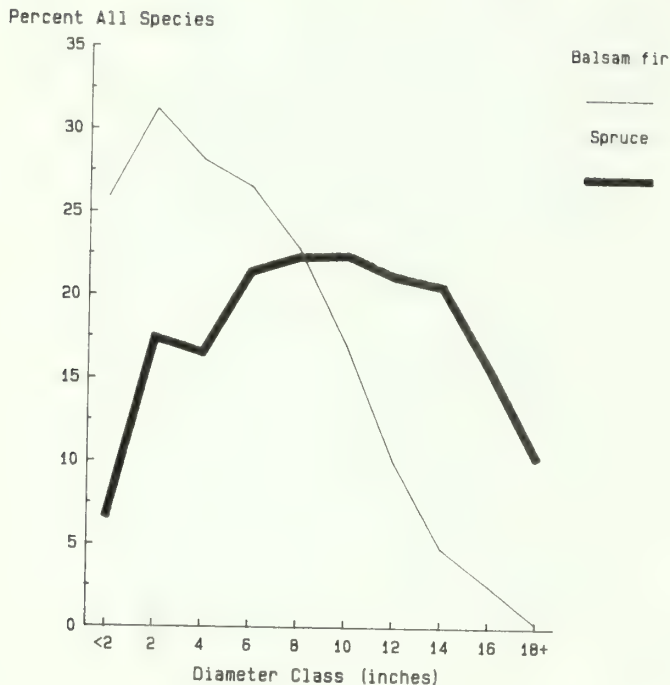


Figure 4.--Percentage of all live trees of all species by diameter class for balsam fir and spruce in Maine, 1982.

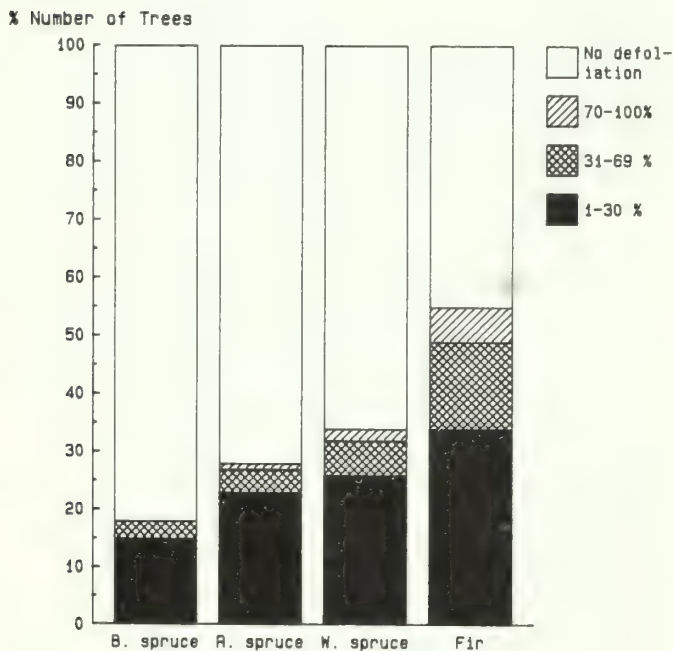


Figure 5.-- Defoliation classes for black spruce, red spruce, white spruce, and balsam fir in Maine, 1982.

spruce (28 percent), white spruce (34 percent), and balsam fir (55 percent). This supports the hypothesis that balsam fir is the preferred host of the budworm, and that spruce species (especially black) are less favored hosts (Baker 1972). Note that for all species the most common defoliation class besides no defoliation is the lightest one, 1 to 30 percent.

The defoliation of the spruce-fir resource is uneven across Maine (Fig. 6). The state average shows that 40 percent of the trees are defoliated to one extent or another. The most defoliation was found in Piscataquis County where 53 percent of the spruce and fir growing-stock trees showed some defoliation. Trees in southern and western areas had the least defoliation damage. But, defoliation does not translate directly into volume loss as we will see later.

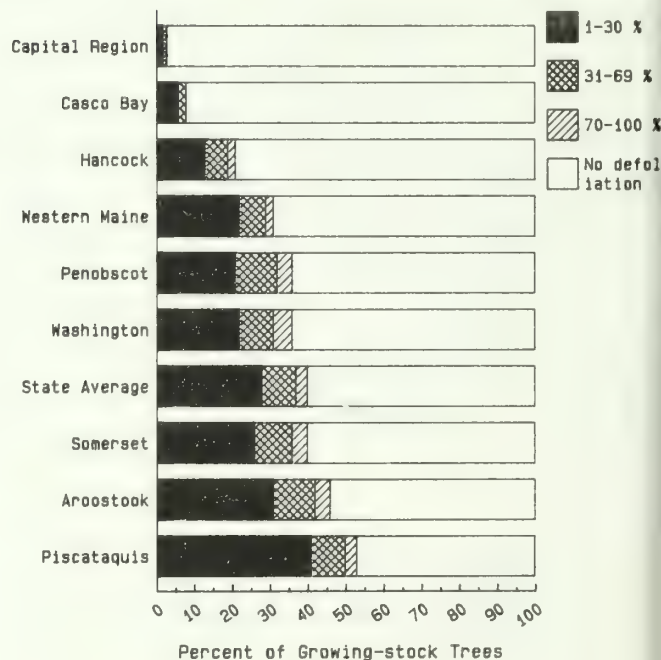


Figure 6.--Defoliation classes for spruce and fir combined by geographic unit, Maine, 1982.

Now we will turn our attention to the volume of the species and how it has changed over time.

In 1982, spruce and fir growing-stock volume amounted to 9.8 billion cubic feet or about 115 million cords. This is 43 percent of the volume of all species in Maine. In 1971, spruce-fir volume was 10.5 billion cubic feet, which was nearly 50 percent of the state's total volume. Between these surveys the growing-stock resource suffered a 7 percent decline (Table 1). The fir volume was the reason for this as it fell by 20 percent over the 11-year period. Spruce held its own (the 5 percent increase was not statistically significant). During the pre-budworm period between 1959 and 1971, the volumes of both fir and spruce registered significant gains.

Because of these different changes, the composition of the spruce-fir resource shifted. In 1971, balsam fir accounted for 48 percent while spruce was 52 percent (red spruce - 44, white spruce - 6, and black spruce - 2). By 1982, the fir proportion was down to 41 percent and spruce had increased its share to 59 percent (red spruce - 49, white spruce - 6, and black spruce - 4). Notice that the 1959 distribution was nearly identical to the 1971 distribution. As we will see later, these changes are the results of many factors, but undoubtedly, the spruce budworm outbreak had a significant impact.

Besides the shifts in species makeup, the spruce-fir growing-stock resource also changed within diameter classes (Fig. 7). Between 1959 and 1971, spruce and fir volume increased in all diameter classes. Between the last two surveys, increases were limited to trees in the 10-inch class and larger. Major decreases occurred in the pole-timber-size trees, especially in the 6-inch class. This resource is characterized by small trees, so if the volume is dropping, one might expect that small trees would be affected. But these small trees are also often old trees growing in overstocked stands. Such trees are certainly susceptible to suppression and natural decline. But the budworm also finds these stressed trees likely hosts, and it damages this segment of the resource more than others.

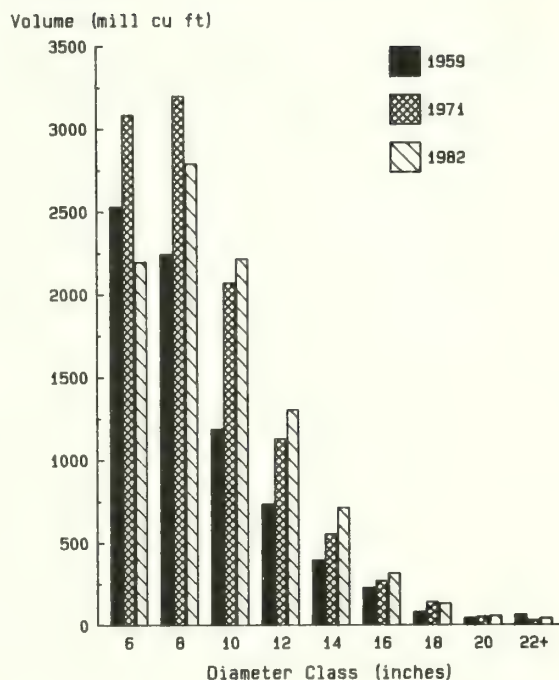


Figure 7.--Spruce and fir growing-stock volume by diameter class, Maine, 1959, 1971, and 1982.

Table 1. The spruce-fir growing-stock volume in Maine.
(Volume in billions of cubic feet)

Species	1959	1971	1982	Change ('71 to '82)
Fir	3.6 (47%)	5.0 (48%)	4.0 (41%)	-20%*
Spruce	4.0 (53%)	5.5 (52%)	5.8 (59%)	+ 5%
Total	7.6 (100%)	10.5 (100%)	9.8 (100%)	- 7% ^a

^aSignificant change ($p=.67$)

The sawtimber resource is a subset of the growing-stock resource that is most suited to use by the sawmill industry. In our definition of sawtimber, the smallest trees are 9 inches in diameter. This volume is expressed in terms of board feet. As might be predicted from figure 7, the sawtimber volume of spruce-fir has increased steadily from the initial inventory. In 1959 the volume was 11.2 billion board feet, in 1971 it was 15.8 billion board feet, and in 1982 it was 19.2 billion board feet. Between the second and third inventories, while growing-stock volume was declining by 7 percent, sawtimber volume was gaining 22 percent. So, despite the overstocked stands, the budworm outbreak, and the substantial harvesting activity the larger sized trees did surprisingly well. This is why we are seeing an increase in the area of spruce-fir sawtimber stands. Thus, a resource that is considered relatively old by some people is continuing to grow and mature.

There is certainly a dark cloud on the horizon of sawtimber volume, however. The ingrowth to this resource must come from the pole-size diameter classes, and these have shown drastic reductions between 1971 and 1982. By the time our next survey is conducted, these reductions should affect spruce-fir sawtimber volume.

Figure 8 shows where the growing-stock and sawtimber volumes of spruce and fir are concentrated in Maine. The values are expressed in terms of volume per acre of timberland rather than total spruce-fir volume. Piscataquis County, besides being the heart of the state, also seems to be the major spruce-fir area. The ranking reflects a combination of the natural growing conditions and the past history of man's activities in the various regions.

More On Growing-stock Volume Change

The growing-stock resource of spruce and fir is declining. But as with other attributes of this resource, the statewide situation is an average of conditions, which differ around the state. Most geographic units showed insignificant changes (Fig. 9). In absolute terms, Aroostook County lost the most volume, 470 million cubic feet. But in percentage terms, Penobscot County fared the worst with a 27 percent decline.

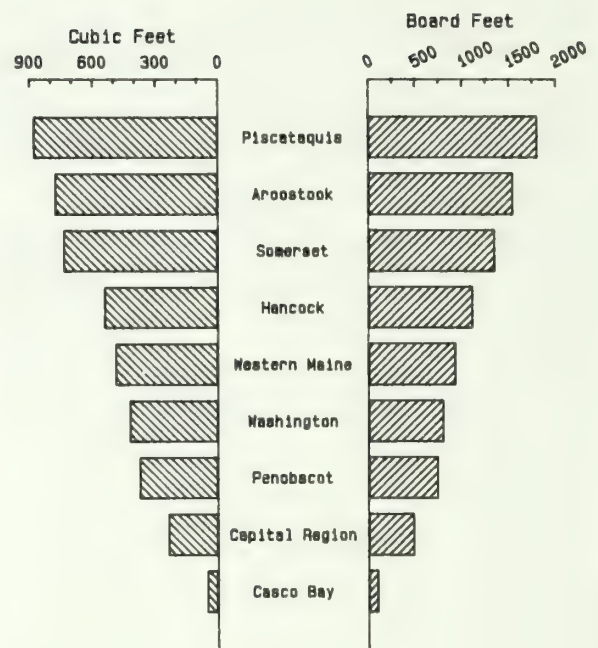


Figure 8.--Spruce and fir volume per acre of timberland by geographic unit in Maine, 1982. The state average on all timberland areas was 575 cubic feet per acre and 1,128 board feet per acre.

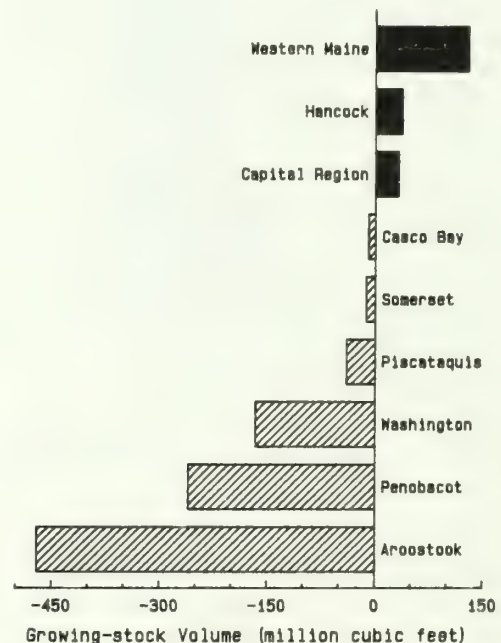


Figure 9.--The change in spruce and fir growing-stock volume between 1971 and 1982 in Maine by geographic unit. Only Washington, Penobscot, and Aroostook counties showed significant change.

It is interesting to compare figures 6, 8, and 9 to see what relationships exist between defoliation, volume per acre, and change in volume. Piscataquis County is a good illustration. It had the worst defoliation conditions and yet it ranked first in terms of volume per acre and showed little change in volume between 1971 and 1982. The degree of defoliation was not well correlated to either volume per acre or volume change. One explanation is that the defoliation conditions may have been relatively recent, while the volume change was calculated over an 11-year period. Another is that even if defoliation translates directly into mortality, mortality is only one of several components that determine the net change in volume.

The annual net change in volume is equal to the difference in inventory estimates divided by the number of years between the inventories. Net change is equal to net growth minus removals. Net growth is equal to gross growth minus mortality minus cull increment (the volume of live trees that were merchantable but are now cull). Gross growth is equal to ingrowth (the volume of trees crossing the 5-inch diameter minimum) plus accretion (the growth on trees that were alive and merchantable at both occasions).

A comparison of these components for fir and spruce will permit a fuller understanding of why the volumes changed as they did between the last two inventories. In figure 10, the components of change are listed across the top of the chart. The circles represent volume of fir, spruce, or spruce and fir combined. The area of the circles is drawn in relation to gross growth, which is set at 100 percent. Empty circles represent positive values, and filled circles represent negative values.

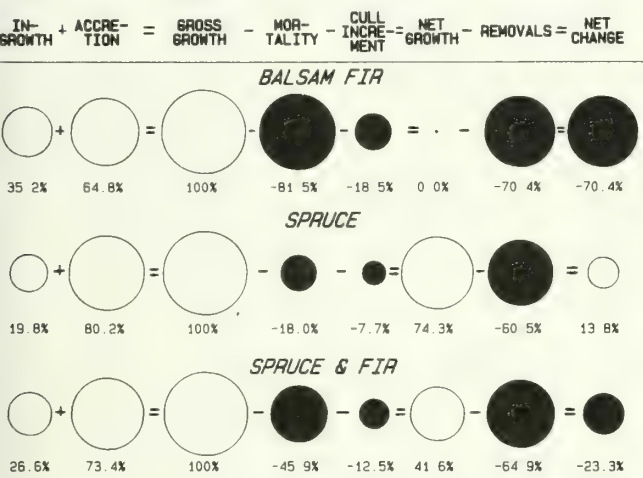


Figure 10.--Components of annual net change for balsam fir, spruce, and spruce and fir in Maine for the period 1971-1981.

For example, balsam fir gross growth is 35 percent ingrowth plus 65 percent accretion. Gross growth is then reduced 82 percent by mortality and another 18 percent by cull increment. This leaves essentially zero in terms of net growth. When removals, which is 70 percent the size of gross growth, is subtracted from net growth, the result is a negative net change that is 70 percent the size of gross growth.

Another way to look at this is in terms of walking along a path. We begin walking, and after accounting for ingrowth and accretion, we have moved ahead 100 steps. We are hit by the fierce wind of mortality and cull increment, and we are blown back to near our starting point. This is net growth. After a brief respite, we are moved backwards another 70 steps by chain saws and feller-forwarders (removals). Where we finally stop is net change. That sequence was repeated each year for fir in Maine during the last period between inventories.

Comparing the components of annual net change for fir and spruce reveals some interesting differences and similarities. While accretion contributes more to gross growth for both species, it is larger for spruce than fir. Ingrowth is more important to fir because the fir resource, as shown in figure 4, has more small trees. These small trees eventually grow large enough to cross the 5-inch threshold, and are then counted as ingrowth. The spruce resource is dominated by larger trees, and more of its growth is put on these trees, which counts as accretion.

The mortality level for fir is much larger than it is for spruce. This was partially reflected in figure 3 in terms of dead trees. Two factors are important here. One is that fir, in comparison to spruce, is a short-lived species. In many stands, the spruce and fir trees are the same age, but the fir is becoming overmature while the spruce has yet to reach maturity. Thus, the fir are dying at a faster rate than the spruce. Another factor is the budworm, which damages the fir component of this resource most severely (Fig. 5). These two factors no doubt contribute to the much greater impact of cull increment on fir than on spruce. Aging and budworm may first cause a tree to be unmerchantable before it finally succumbs.

The difference in net growth is most noticeable. While fir is at a standstill, spruce is increasing at a level three-fourths of gross growth. The negative impact of mortality and cull increment was much greater for fir. Even without the impact of harvesting, fir in Maine is going nowhere.

The removals component was relatively high for both species probably because of the increased industrial expansion of the wood-using plants in the region. Substantial harvesting pressure is being applied to both species. The fact that fir's removals percentage is greater than that of spruce may be a reflection of the impact that spruce budworm has had on the harvesting practices of the spruce-fir landowners. Proportionately more fir was being harvested in sanitation and salvage operations. Spruce was considered to be less vulnerable to budworm attack so it was sometimes left in the stands for cutting at a later date.

The bottom line, net change, is consequently different for fir and spruce. Fir is substantially negative, while spruce is modestly positive. Even though the situation is better for spruce than fir, it would only take slight decreases in gross growth and/or slight increases in mortality, cull increment, and removals to reduce net change to zero or a negative value. If indeed the budworm is killing spruce trees and reducing growth on live trees more now than it did between 1971 and 1981, then spruce might today be at the breakeven point.

If we compare certain components of change for the pre-budworm outbreak period (1958 to 1970) with those for the post-budworm outbreak period (1971 to 1981), we see that some radical shifts have occurred. In Table 2, the annual components are taken as a percentage of the spruce-fir growing-stock volume. These could then be viewed as annual rates of change, similar to the interest or yield one might receive on an investment. The mortality rate for spruce-fir has nearly doubled. The net growth is less than one-third of what it used to be. Removals have increased significantly, especially for fir. And net change has moved from a robust 2.4 percent increase to a negative 0.6 percent. This indicates that a peak of growing-stock inventory occurred somewhere between 1971 and 1981. What was going up is now coming down. Not all of these changes were caused by spruce budworm, but it undoubtedly was an important factor affecting each component and each species.

Table 2. Some components of annual change as a percentage of spruce-fir growing-stock volume.

Components	Fir	Spruce	Spruce/fir
		Percent	
Mortality			
1958 to 1970	-1.1	-0.4	-0.7
1971 to 1981	-2.2	-0.5	-1.3
Net Growth			
1958 to 1970	+3.8	+3.7	+3.8
1971 to 1981	0.0	+2.1	+1.1
Removals			
1958 to 1970	-1.2	-1.5	-1.4
1971 to 1981	-1.9	-1.7	-1.8
Net Change			
1958 to 1970	+2.6	+2.2	+2.4
1971 to 1981	-1.9	+0.4	-0.6%

Summary and Conclusions

The spruce-fir resource in Maine dominates the state's timberland. It has dominated for centuries and it will continue for centuries. What we are witnessing now are the shifts and changes of a dynamic ecosystem. Pressures of varying degree are being applied from several sources and directions.

The stands are becoming more diverse in species composition though they will always be predominantly spruce and fir. The stands are crowded with trees and have become more so within the last decade. The aging and competition within the stands, in conjunction with feeding by the spruce budworm, have led to more dead trees in the stand. A combination of natural death and harvesting has reduced the numbers (and volume) of the pole-size trees in a resource dominated by small trees.

Spruce and fir, while often mentioned in the same breath due to their close association in the woods, are really two different species that are dissimilar in many respects. They have different silvical characteristics. They do not live the same length of time. In unattended stands, fir tends to dominate the small size classes and spruce the larger ones. They are not treated equally by the budworm and, to a certain extent, by man.

The challenge to the forestry community is not how to preserve the spruce-fir resource because that is, in different senses, both impossible and unnecessary. The challenge is to recognize which pressures are affecting the resource, what the nature and extent of these pressures are, and how to then manage these pressures in such a way as to maintain an adequate flow of products and benefits from this renewable resource. It is not an easy job, but it is one that we, as professionals, can tackle and complete.

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THE INVENTORY EFFECT OF SPRUCE BUDWORM IN NEW BRUNSWICK

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Introduction

Once upon a time the spruce budworm was not a problem in New Brunswick. We had a spruce/fir forest and we had spruce budworm, but as our francophone friends in Canada say, it was "pas de probleme". The forest industry in eastern Canada had developed on a base of white pine, a species fortunately not plagued by serious pests like spruce budworm. As white pine disappeared from our forests in the late 1800's and early 1900's, spruce and fir became more prominent components of the forest, and the industry shifted its attention to these species. Forest composition and industrial demand evolved together, and by the early 1950's a major pulp and paper and sawmilling industry had developed, with the spruce/fir forest as its mainstay. Of course the spruce budworm had been there all along. There is evidence that our forests have experienced at least seven major outbreaks in the past 200 years. Those outbreaks took their toll, but until the 1950's there was sufficient growing stock to satisfy the appetites of both the budworm and man. In other words, we had a clear surplus of spruce/fir growing stock. This is evident in a 1935 report by Miles Gibson, describing the condition of the forest after the 1912-1920 epidemic.¹

"The amount of loss that resulted and the present conditions of these areas are hard to realize without a personal visit, for it is difficult to visualize areas that have not been cut for at least 40 years with 90% of the mature fir and spruce lying on the ground in various stages of decay almost hidden among a dense stand of spruce and fir up to 20 feet in height".

The current epidemic in New Brunswick which began about 30 years ago, is simply a continuation of the spruce/fir forest-budworm cycle which has been repeating itself for centuries. The factor which sets this current epidemic apart from previous outbreaks is that the industry has developed a high economic dependence on the same species favoured by the spruce budworm.

This dependence, of course, was the rationale behind the decision to initiate a protection spraying program in 1952; some 30 years later, this economic dependence continues to be the justification for annual protection spraying.

New Brunswick's Softwood Inventory

New Brunswick carried out three provincial forest inventories in 1958, 1968, and 1979. In addition, about 1100 permanent sample plots were established in 1955 and maintained since. Inventory data provide a good basis to track growing stock development over 20 years. Before discussing this, it is important to emphasize that during this period the forest was under continuous pressure from budworm, but it was also protected annually through spraying. So what we have generally is a picture of growing stock development in which the natural budworm-forest interaction was suppressed through spraying. This was a new experience for the spruce/fir forest of New Brunswick.

In the early 1950's, most of the softwood forest on Crown land (predominantly spruce and fir), was in the 30 to 50 year age class; this was the forest that resulted after the 1912-1920 budworm outbreak. By 1979, this age class had matured and now, the 60 to 80 year age class occupies 76% of Crown land.

If this forest had been uninfested and grown normally, we expect development would have peaked in the 1960's and then started to decline rapidly in the 1980's, due mainly to fir mortality (Fig. 1). The presence of budworm in this forest has simply accelerated this decline.

Table 1 shows the total merchantable softwood inventory from 1958 to 1979 for the province as a whole, and for the northern and southern halves of the province. From 1958 to 1968, the total softwood inventory increased by 18%, but in the following decade, the inventory declined to about the same level as in 1958.

Of interest is the difference in development of spruce and fir, during that period. In the first decade, the spruce inventory increased twice as much as fir (24% vs. 11%), and in the second decade fir decreased more than twice as much as spruce (22% vs. 9%).

An examination of the trends in growing stock in northern and southern New Brunswick shows that:

1. the major gain in growing stock has been on spruce in southern N. B.
2. the major loss in growing stock has been on fir in southern N. B.

¹Gibson, J. M. 1935. Report of an inspection of the Restigouche Company land on the Kedgwick River watershed. Unpubl. Rep., N.B. Dept. Lands & Mines.

Figure 1

Expected development of predominantly Fir and predominantly Spruce stands after 1912 Budworm epidemic, assuming no further insect attack.

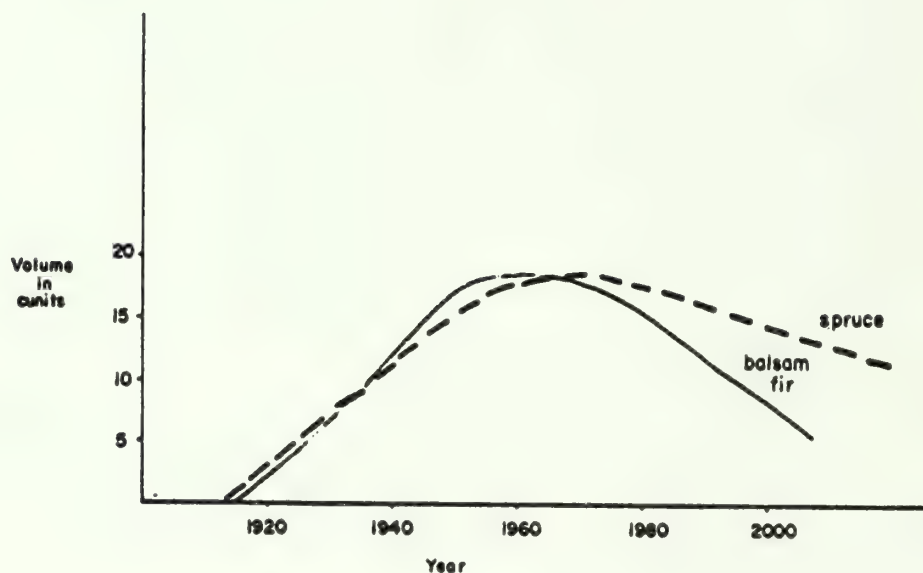


TABLE 1. MERCHANTABLE SPRUCE AND FIR GROWING STOCK IN NEW BRUNSWICK, 1958 to 1979
('000 cunits)

PROVINCIAL TOTAL

	Growing Stock			Change in Growing Stock		
	1958	1968	1979	1958 to 1968	1968 to 1979	1958 to 1979
Spruce	5180	6453	5859	+1273 (24%)	- 594 (9%)	
Fir	5151	5713	4468	+ 562 (11%)	-1245 (22%)	
TOTAL	10331	12166	10327	+1835 (18%)	-1839 (15%)	

NORTHERN NEW BRUNSWICK

Spruce	3305	3600	3047	+ 295 (9%)	- 553 (15%)	-258
Fir	3714	3896	3522	+ 182 (5%)	- 374 (10%)	-192
TOTAL	7019	7496	6569	+ 477 (7%)	- 927 (12%)	

SOUTHERN NEW BRUNSWICK

Spruce	1875	2853	2812	+ 978 (52%)	- 41 (1%)	+937
Fir	1437	1817	946	+ 380 (26%)	- 871 (48%)	-491
TOTAL	3312	4670	3758	+1358 (41%)	- 912 (19%)	

In the north, the fir growing stock has declined by 374 000 cunits in the last decade, a drop of 10%, but in the south, the inventory of fir has decreased by 871 000 cunits or 48%. Over the 20 year period, the fir inventory has decreased by only 192 000 cunits in the north, compared with 491 000 cunits in the south.

Development of spruce presents a different story entirely. In the south, the growing stock of spruce decreased by only 1% in the last decade, compared with a 15% decline in the north. Over the 20 year period, the spruce inventory increased in the south by 937 000 cunits, compared with a decrease of 258 000 cunits in the north.

The Effect of Spruce Budworm

The reason for considering growing stock development in the south separate from the north relates to the difference in protection from spruce budworm in the two parts of the province. Until 1976, the spruce/fir forest was protected throughout the whole province with an annual spray program. However, in 1977, the New Brunswick government imposed what amounted to a one-mile setback zone around all human habitation in the province, preventing the aerial application of chemical insecticides in this zone. The result was that for four years, the forest in this setback zone received no protection from budworm. Because southern New Brunswick is much more heavily inhabited, in both urban and rural areas, much more of the softwood forest went unprotected in the south than in the north. In fact, over 75% of the southern forest was removed from the protection spraying program.

Since 1981 protection has been restored to part of this one-mile setback zone, using small aircraft. However the effect of not protecting balsam fir for four years has been dramatic. Approximately half the inventory of balsam fir disappeared between 1968 and 1979, and the majority of this loss is attributable to spruce budworm.

Data from permanent sample plots reinforces the effect of lack of protection on growing stock. Figure 2 shows the growth of the spruce and fir components in a plot located in north-central New Brunswick (plot 9-3). This plot is in a stand which has been protected as required, and is now 70 years old. In contrast is a plot (plot 2-a) in an area that was unprotected due to environmental setbacks (Fig. 3). This graph shows the budworm effect on inventory clearly, with a sharp decline in fir growing stock in the late 1970's, while the spruce growing stock remained static.

This response of fir to lack of protection will surprise no one. Balsam fir is noted for its vulnerability to spruce budworm feeding. Four to five consecutive years of severe defoliation is enough to kill this species.

In contrast, spruce is more tolerant of budworm feeding damage than fir, and this is evident in the negligible loss in spruce growing stock (1%) in southern N.B. from 1968 to 1979, despite the lack of protection.

What is the future effect of the budworm likely to be on merchantable volumes of spruce and fir? In the mature forest where protection is possible, the budworm may become of secondary importance to the natural volume declines due to over-maturity of the forest. By 1990, most of the fir-spruce forest will be in the 70-100 year age class. This is not critical for spruce but fir volume is expected to decline rapidly regardless of budworm attack.

In the long run, the effect of budworm on the younger forest is perhaps the most critical problem facing New Brunswick. These young stands are scheduled for harvest, starting 30 years from now and if budworm caused mortality or growth losses delay or reduce the availability of this wood, there will be severe wood shortages in the Province for a 8-10 year period beginning about 2020. This is illustrated in Figure 4. The difficulty is that the majority of this immature softwood is located on small freehold land, nearly all of which is located in the setback zone where environmental constraints make effective protection spraying more difficult, and more costly.

We have a very tight supply situation for softwood for the next 30 years. We will have no surplus, and virtually every merchantable softwood stand in the province is required to sustain industrial demand during that period. Our strategy in New Brunswick is to direct harvesting into fir and fir/spruce stands rather than into spruce or spruce/fir, and to restrict harvesting to the mature-overmature stands. As well we are directing protection spraying to mature stands that can be maintained in an operable condition, and to immature softwood which will be required for harvest in 15 to 20 years.

This has forced us into management of individual stands, something which is impossible with traditional forest inventory information. However, a new computer mapping system recently acquired by the Department of Natural Resources is making this possible.

In summary, the effect of budworm alone on spruce and fir inventory is very difficult to document. There are reports from the Canadian Forestry Service on how much wood is dead or dying in various jurisdictions. The Department of Natural Resources itself carried out a similar survey in 1981. The numbers are very impressive - 17 million cunits of moribund or dead spruce and fir in the province, or six times the amount we harvest annually. In New Brunswick the amount of dead wood, however, is only of academic importance. The critical thing to know

is the amount of merchantable softwood volume that can be expected over time, and what level of protection of current growth is required to achieve this production. Making this happen will require more than protection. We must rigorously schedule our harvesting so that the inventory of mature softwood does last until about 2020 when our new forests are expected to become operable. In the meantime, utilization will have to be improved and lower volume stands harvested in order to carry us through the next 35 years.

FIGURE 2

Growing stock development in forest area protected from spruce budworm.

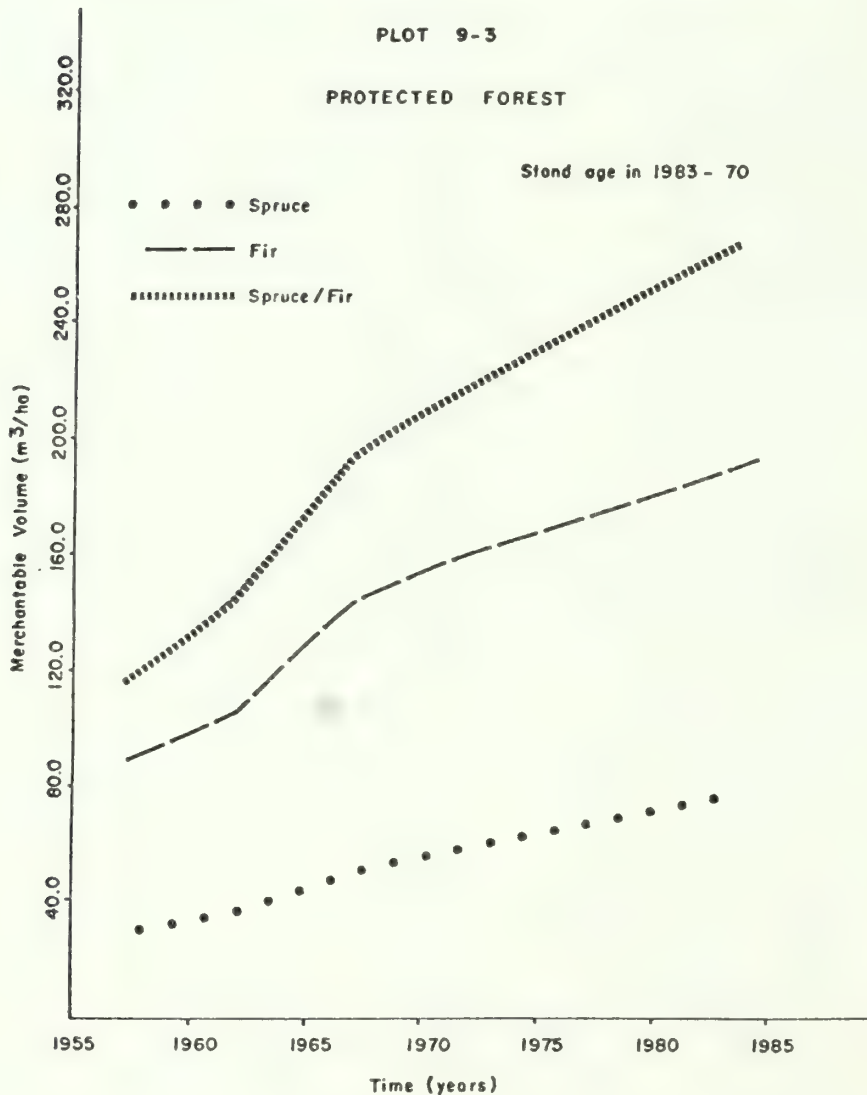


FIGURE 3
 Growing stock development in forest area with no protection from budworm
 from 1977 to 1981.

PLOT 2-1

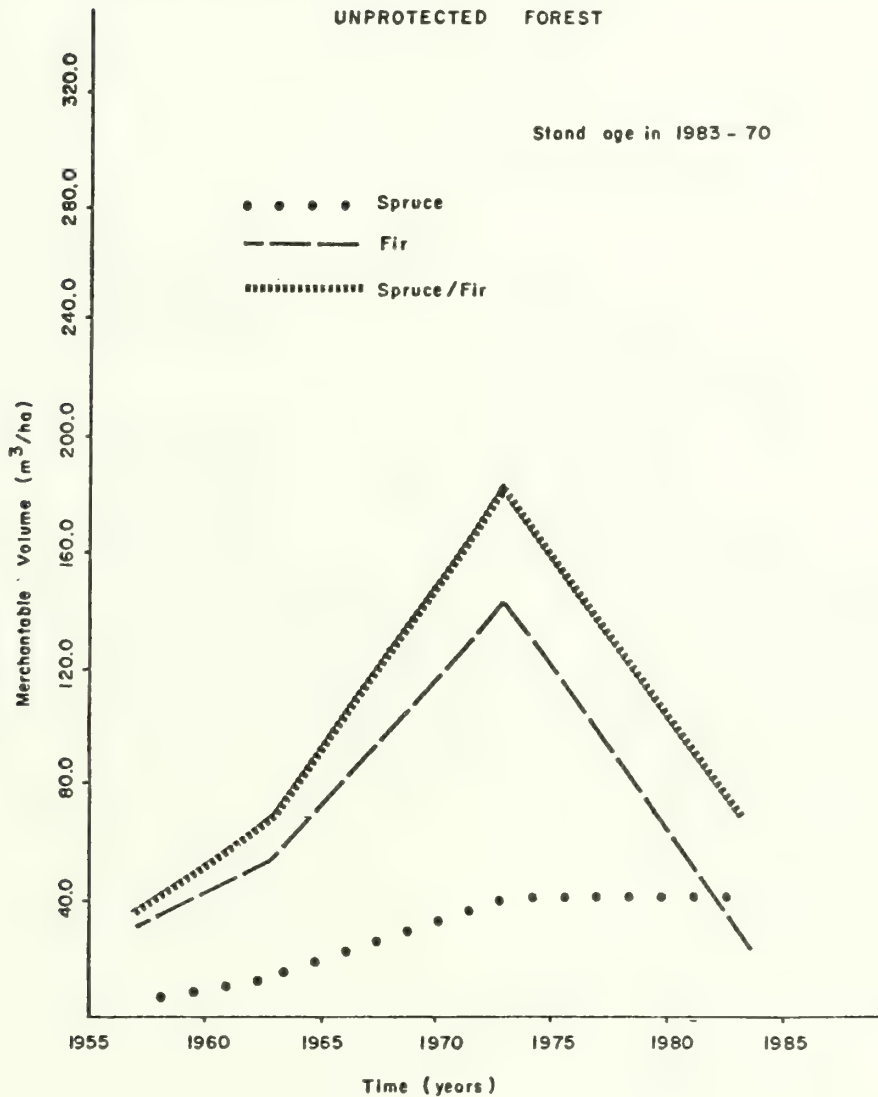
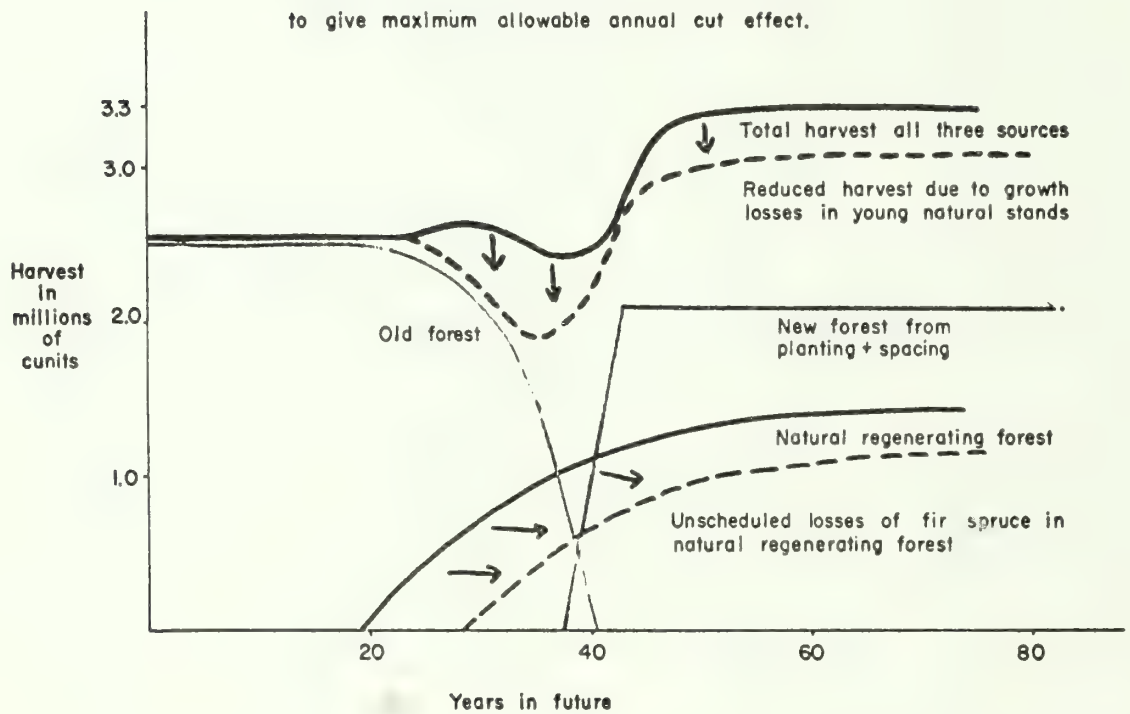


Figure 4

Available harvest with silviculture program level set
to give maximum allowable annual cut effect.



Thomas J. Corcoran and Harvey M. Schiltz

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A computerized system, motivated by the need for budworm-related wood procurement strategies, was developed in stages. The initial mapping and information storage/retrieval program was expanded to provide an automated technique for selection of timber harvest sites and determination of scheduled wood flow to associated market locations. An extension to the system implemented an interactive computer graphics module that assists in the optimization of the harvest area spatial layout of all-weather logging roads and associated decentralized processing locations (landings). Further expansion led to the development of a total map-based information system, with features complimentary to the initial data-base that provides inventories of road networks to allow more accurate forecasting of harvest/transportation costs.

The spruce, *Picea* spp., and balsam fir, *Abies balsamea* L., are important components of northern New England's forest ecosystem. In Maine, spruce-fir forests cover some 8 million acres of 47 percent of the State's forestland. The economic importance of Maine's spruce-fir resource is indicated by its annual harvest of more than 2.2 million cords of pulpwood and 600 million board feet of sawtimber (Field, 1980). Between 1975 and 1980, spruce and fir mortality amounted to nearly twice the harvest of these species (Schiltz et al., 1983). Thus, the current spruce budworm, *Choristoneura fumiferana* Clem., epidemic potentially necessitates the salvage of large quantities of the spruce-fir timber resource.

Program Initiation

An inventory system has been established to monitor spruce budworm infestation severity. To facilitate handling of the inventory data, a computer program was developed to tabulate and display information on budworm levels and stand conditions. The program produces lineprinter maps showing the distribution of budworm hazard ratings throughout the State or any portion of it. The lineprinter maps are based on grid coordinates which divide the State into rectangular units of approximately 240 hectares. These rectangular units are one minute by one minute subdivisions of U.S. Geological Survey 15-minute quadrangle maps and are referenced by State fire control division designations. Although survey information is lacking for smaller subdivisions, the mapping routine will produce maps down to ten acres. Each map character - a dot, letter, number, or other symbol - represents the center of one rectangular unit (cell). In addition to indicating high population levels, budworm hazard ratings

are used to determine areas potentially in need of timber salvage operations.

System Expansion

During the development of the tabulation and mapping program, routines were included that allowed the construction of an automated technique for selection of timber salvage sites, transportation network routing, identification of markets, and the optimum cost allocation of wood volumes to specified destinations. The system's construction allows numerous overlays of data to be associated with each identifiable data-point, based on the grid layout. A data-point can contain overlays of information on existing roads, infestation severity, wood volumes, and market locations. Information storage/retrieval flexibility allowed the development of intricate data manipulation routines. These routines include the simulated creation of new roads to access timber salvage sites, a transportation routing technique, and the "classical" linear programming transportation model.

System Methodology and Execution

Specification of boundary cells and transportation network segments comprising the selected base area is required for initiating program execution. Additionally, the potential salvage sites, as identified by pre-selected criteria (eg. infestation severity ratings), require associated timber volume input.

In the second execution phase, routines manipulate the selected data-base connecting all potential source locations (salvage sites) to the existing transportation network. Beginning at the salvage site with the shortest distance to an existing road, a new road is theoretically built. Subsequent passes re-sort the source location data allowing newly constructed roads to be shored by multiple source locations, thus minimizing new road construction. Once all source locations are connected to road network, a shortest path network analysis technique calculates the minimum transportation cost per unit volume from each source to each destination. This process begins at a destination or market location and proceeds outward along the transportation network. The product of the cost per unit distance for each road class and the linear distance between grid cell centers is sequentially summed to provide transportation costs for each source/destination pair. The process continues until all source locations are "costed" or all elements of the transportation network connected to the destination have been processed (Phillips, Corcoran and Brann, 1983).

Lastly, the calculated costs, salvage site volumes, and mill (destination) requirements are utilized in the linear programming transportation model. The result is a list of salvage sites allocating their associated timber volumes to specified market locations. The total transportation cost is the minimum cost obtainable, while still satisfying the constraints of supply and demand. The

Proceedings of a Conference "FROM STUMP THRU MILL" provides an overview of the need for effective transportation planning and efficient utilization of the spruce-fir resource (Corcoran and Gill, 1983).

Harvest Site Planning

A modular component of the system deals with the layout of roads and landings at the salvage site. When salvaged timber is skidded to a road-side landing and roads are laid out - roughly parallel and equally spaced - optimum road spacing is a function of road construction cost, variable skidding cost and landing development cost (if applicable). Standard computational factors include such notation averages as machine speed and load size, operating area designation, timber volume, travel patterns and distances plus costs of road construction, of landing construction, and of relevant machine useage. When manipulated mathematically, they produce as a defined cost-optimum, the spacing between parallel roads and between the systematically located landings. Solution of the model involving multiple unknowns required a heuristically interactive procedure. A mathematical model developed to determine the ideal spacing arrangements and their effect upon costs (Ashley, et al., 1973), became the basis of the graphics procedure outlined below.

Once salvage sites have been selected, an interactive computer graphics routine provides assistance in optimizing the spatial layout of logging roads and landing locations over the harvest area. (Corcoran and Bryer, 1982). The routine allows the operator to input data values, within pre-determined limits, and the program calculates and displays the optimum road and landing spacing and associated costs. In addition to tabular output, the routine allows the production of grids that can be used as overlays on aerial photographs or maps (developed by computer displays) in the initial stages of harvest site planning. Furthermore, unusual ramifications of road/landing layout patterns have been described by Bryer (1983).

Description Data-base Integration

As an outgrowth of the "road building" and harvest area spatial layout routines, a map based information module combining layers of map data with related non-graphic data has been organized as a data-base. The structure of the new module includes a road description data-base with parallel linkage to the existing location data-base. The description data-base contains all alphanumeric data associated with the road network. This data includes road names, road numbers, lengths, widths, curve-radii, pavement types, grades, functional class (primary haul, secondary haul, spur, light vehicle) and maintenance information. Descriptive data for special structures (bridges, culverts, intersections) is also stored in the description data-base, while the location data-base has been expanded to accomodate location data for these structures.

The linkage between location data and descriptive data allows a wide range of maps and reports to be requested, entering from either data-base. The graphics sub-system can be used to identify an area of interest and provides indirect access to the data-base. All data or some subset of the descriptive data pertaining to that area can be displayed. Furthermore, a map can be plotted displaying the location and extent of the features or areas selected during the data-base search, using the graphics routines.

Other report request capabilities include basic road mapping, road identification, road and material specifications, maximum loads for specified travel routes, maintenance planning, (minimum) travel time and distance estimates between two points, and exception reports providing the location and description of all road segments and structures where structural and functional specifications do not coincide. Also, the impact of environmental and other land-use regulations on road networks will be readily available (e.g. protected buffer zones associated with roads or water ways).

Expansion of the map based information module to include landform features and terrain considerations in the new road location algorithm, will require a three dimensional representation of the area to be stored in the location data-base, which currently holds two dimensional data. This feature will enhance the planning of road networks and allow more accurate determination of transport equipment limitations, harvest/transportation costs and wood flow schedules.

Discussion

Successful application of the entire system requires diverse information about potential harvest sites, timber volumes, existing road networks, market locations, market requirements, and landform features. Although detailed information for all parameters is not yet completed on a State-wide basis, each segment of the system is independently useable where the appropriate data is available. In the recent past, the system operatively utilized estimated salvage volumes, estimated road costs, and budworm survey data to provide total timber volume allocation and associated costs. Into the year 1984, a U.S. Forest Service grant (CANUSA) financially supports the system's utilization as a research tool in developing harvest scheduling procedures.

While development was motivated by a forest insect problem, the system's inherent flexibility provides high potential for more generalized use. Whenever the short-term timber supply in need of harvesting is in excess of market requirements (supply > demand), the association of timber sources with market locations - based on a cost minimization - can be utilized to determine where harvesting should be concentrated. Conversely, specific markets that are allowed to participate in a limited short-term supply (demand > supply) can be defined and quantified.

The techniques applied in this system should be readily adaptable to other regions or nations, particularly where the forest resource is quite extensive, roads are limited, and the timber sources and delivery locations are usefully differentiable in terms of macro-policy, whether the policy goals be publicly or privately motivated.

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USING FOREST INVENTORY AND COMPUTER SIMULATION TO EVALUATE HARVEST SYSTEMS

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The productivity of two chipping systems were simulated and compared based on two different feller-bunchers: tracked machines with a rotating boom-mounted shear, and rubber-tired articulated machines with a fixed front-mounted shear. Identical sets of simulated grapple skidders and chippers were combined with both feller-bunchers. Although the same machine speeds were assumed for both systems, outputs were compared for different shear capacities and machine availabilities. Several new procedures are illustrated.

Using inventories to assess harvest equipment requirements was the primary task of early timber cruisers. They estimated volumes as well as recommended how and when the timber should be extracted. In this report I evaluate two harvest systems using inventory data from northeast Minnesota. But while the timber cruiser in the past had only his experience to recommend what system or systems would be most appropriate, we have several other tools at our disposal. Specifically, simulation and data base management techniques can be used to model the interactions of machines, operators, and stands. And, at least in theory, we can learn which harvest systems are best under various stand conditions.

This study was funded by the CANUSA program and is a hypothetical yet realistic analysis of stand and tree factors, machine capabilities, and operating rules. Only a limited range of equipment and stands could be considered in the time available, but this report identifies the effect of certain decisions made by machine operators in their tree-to-tree and bunch-to-bunch movements. Productivity can be increased and cost reduced if simple rules are applied as tree and stand factors change.

Scope

Two different feller-bunchers working with the same set of two grapple skidders and one chipper were examined using three simulation models developed by the North Central Forest Experiment Station (NCFES).

We did not collect any machine speed and capacity data. Instead, the NCFES Forest Engineering Unit in Houghton provided its best available data. For the tracked feller-buncher,

the grapple skidders, and the full tree chipper, we assumed only one set of speeds and capacities. For the rubber-tired feller-buncher, we assumed one set of speeds but two shear capacities.

Similarly, we did not collect any new stand data. Instead, we examined the NCFES's most recent forest inventory data for northeast Minnesota to find all plots with fir-spruce stocking. From these plots, we constructed 12 hypothetical stands representing average stand diameters of 6, 8, and 10 inches and basal areas of 60, 90, 120, and 150 square feet per acre. These 12 combinations represented about 95 percent of the stands in northeast Minnesota with more than 20 percent fir and spruce basal area. Harvest by the two feller-bunchers, skidding, and chipping were then simulated in each of the 12 stand combinations for the relations between productivity and the independent variables of diameter and basal area. Other combinations were used to show the sensitivity of system output to small changes in key operating variables. Finally, a realistic yet much simpler new method of simulating tree-to-tree movements by feller-bunchers was developed that also led to the development of decision rules that may be used to improve rubber-tired feller-buncher performance.

Methods

Discrete event simulation models were used to estimate production under various stand conditions. These models represent the major features of similar real systems: trees, personnel, equipment, and decision rules. Three items were required: (1) stand data for tree locations, diameters and volumes, (2) computer programs to represent machine-man-forest interactions, and (3) machine speed and capacity to estimate tree processing time.

Simulated output was ideal; no allowance was made for machine breakdowns or rest periods, but results were then adjusted to yield so-called "realistic" estimates using machine availability assumptions.

Gathered by observation or theoretical analysis, machine speeds and capacities were not specified absolutely but were randomly sampled from probability distributions for each task (Table 1). In addition, these random samples were controlled to avoid confounding. Although controlling a "random sample" to achieve more rigorous results may seem paradoxical, it is one of simulation's most important advantages.

Stand Data

All northeast Minnesota inventory plots that met several joint criteria of species, diameter, and basal area were examined to find stands most representative of spruce-fir stand conditions. About 1,300 aspen, paper birch, balsam fir, and white spruce plots were examined

and of these 347 were selected. These data were then used to develop distributions of trees per acre, diameter, stem volume, and green weight for 12 diameter and basal area combinations (Tables 2 and 3).

Table 1.--Machine speed and capacity assumptions.

Feller-Bunchers	Tracked	Rubber-Tired
Strip width-feet	34	Variable
Travel speed-mpg	1	3
Shearing speed-cmin/tree	25	25
Bouquet drop rate-cmin tree	15	15
Shear capacity-sum of DBH's	25	25/15

Grapple skidders

Travel speed-mpg	5
Bunch grapple rate-cmin/bunch	75
Bunch realign rate-cmin/bunch	109
Bunch drop rate-cmin/bunch	25
Grapple capacity-sum of DBH's	50

Chipper

Chipping rate-cmin/load	100
Loader capacity-sum of DBH's	25
Van closing rate-cmin/van	50
Van capacity-cu. ft. solid wood	670

cmin = centiminute = 0.01 minute

Table 2.--Tree diameter distributions of stands harvested by simulator.

Average Stand Data			
(Inches)			
DBH Class	6	8	10
(Inches)	(Percent)		
4-5.9	62.7	24.6	8.6
6-7.9	23.6	34.7	23.0
8-9.9	8.4	23.0	26.1
10-11.9	3.3	10.2	19.4
12-13.9	1.2	4.6	11.3
14-15.9	0.4	1.4	7.5
16-17.9	0.2	0.8	2.7
18-19.9	0.1	0.4	0.9
20+	0.1	0.3	0.5
Total	100.0	100.0	100.0

Harvest Models

All harvest simulators used in this study were written in IBM's GPSS V language modified to run on a CDC 172 computer (Bradley et al 1976, 1982, IBM 1973; Winsauer 1980, 1982; Winsauer and Bradley 1982).

Model of a tracked feller-buncher with boom-mounted shear. This model mimicked the

operation of a tracked feller-buncher with an accumulating shear on a rotating boom. A specific machine embodying these characteristics is the Drott 40^{1/}. This type of machine often operates in a straight path -- along the edge of a stand for clear cutting or in a strip through the stand for thinning. In these models both feller-bunchers worked far ahead of skidding so that skidders never waited in the woods. Both feller-bunchers also tried to create capacity bunches for skidding by combining two or more bouquets. However, although the tracked machine did not retrace its steps to drop bouquets on partial bunches dropped earlier, it carried bouquets forward to the next stopping point. In general, this machine: (1) "looked" ahead to see how far it must travel to its next stopping point, (2) moved this distance and stopped, (3) dropped the bouquet when the accumulator was full, and (4) moved again when all trees at this point had been cut (it may only be one tree).

Table 3.--Other characteristics of stands harvested by simulator.

Stand Characteristics				
Average Stand Diameter	Basal Area	Density	Total Stem Volume	Green Weight
(Inches)	(Sq. Ft./Acre)	(Trees/Acre)	(Cubic Ft./Acre)	(Tons/Acre)
6	60	305	2443	56.8
	90	419	3359	78.1
	120	515	4125	95.9
	150	667	5346	124.3
8	60	152	2301	53.5
	90	207	3136	72.9
	120	264	3996	92.9
	150	334	5058	117.6
10	60	75	1901	44.2
	90	102	2585	60.1
	120	135	3419	79.5
	150	167	4232	98.4

Model of a rubber-tired feller-buncher with fixed shear. This model mimicked the operation of a rubber-tired frame steered machine with an accumulating shear fixed in front. A specific machine embodying these characteristics is the John Deere 544. Because this machine must travel to each tree to cut it, it zig-zagged across an arbitrary strip. When its accumulator was full, the bouquet was either dropped at once, carried back and added to an incomplete bunch, or carried to the next tree to be cut and dropped.

Because strip width for this machine was not limited by boom reach as for the tracked machine, a width was chosen, as described later,

^{1/}Mention of trade names does not constitute an endorsement by the U.S. Department of Agriculture.

that minimized the total travel distance. In addition because this machine was modeled to retrace its steps to add bouquets to unfinished bunches, a new question arose: How far back should it go to complete a bunch for skidding? That is, at what distance will system output and profit be largest? This model optimized this decision as stand conditions changed.

Model of two grapple skidders and a whole tree chipper. Bunches, from either feller-buncher, were skidded to the landing and chipped into waiting vans. When each bunch was completed by the feller-buncher, its distance from the landing was recorded along with tree diameters and volume in the bunch. When the skidder found each bunch, it either dragged the bunch to the landing if already large enough, or attempted to add the next bunch on the strip to its grapple. Again, even though a feller-buncher tried to create capacity bunches for skidding, some bunches were still smaller than desired. Once the grapple was full, the skidder returned to the landing for chipping. If another skidder was dropping its bunch or if too many trees were already waiting to be chipped from earlier bunches, the skidder waited. Stock piling bunches elsewhere on the landing was not examined in this simulation. The chipper with loader chipped trees as fast as it could, or as fast as skidders brought wood. Trucking was assumed to be perfectly coordinated so another empty van was ready as soon as one was filled and hauled away.

Simulating tree to tree movements. Both feller-bunchers simulated strip harvests on each of the 12 stand combinations. While developing these models, we devised a new procedure to randomly locate successive trees in these strips. This in turn led to a potentially practical way for rubber-tired feller-bunchers to reduce travel distance and cost by choosing an "optimum" strip width depending on stand density (Bradley et al. 1982). If trees are really randomly scattered, the expected number of trees in any sample area is a Poisson random variable proportional to trees per acre, T . Therefore, when this sample area is a strip, the distance along the strip to the next tree is an exponential random variable inversely proportional to trees per acre and strip width. That is, the mean or expected Y-coordinate distance up the strip to the next tree is:

$$\mu_D = 43,560/TW$$

where T = trees per acre,

W = strip width in feet, and

43,560 = square feet per acre.

On the other hand, the X-coordinate distance of the next tree as measured from the strip's side is a uniform random variable with mean $W/2$. Thus, given strip width and trees per acre, the simulator takes random samples from exponential and uniform distributions to determine the locations of successive trees in the strip.

Optimum strip width for the rubber-tired feller-buncher. While developing these procedures it became clear that an optimum strip width might exist that would minimize travel. In fact, this "optimum" strip width is inversely proportional to the square root of trees per acre:

$$W_{\text{optimum}} = (3(43,560)/T)^{1/2}.$$

For each simulated harvest by the rubber-tired feller-buncher, we calculated the optimum strip width (W) and the corresponding mean Y-coordinate distance between trees (μ_D) for each of the 12 stands in this fashion.

Optimum bunch distance limit for the rubber-tired feller-buncher. The rubber-tired machine was also allowed to retrace its steps to create full bunches, thereby increasing overall system output. The farther it retraced its steps, the less its own productivity but the greater the skidder productivity because bunches were more likely full size. At some distance, however, costs outweighed benefits. The optimum distance depended on the costs of feller-bunching versus skidding and chipping, but precisely how was not clear. However, we conducted an experiment to estimate optimum bunch distance limits for the rubber-tired machine given the speeds and capacities assumed in this analysis. These "so-called" optimums were also used in this study.

Tracked feller-buncher. This machine moved and cut trees in strips somewhat narrower than twice its maximum boom reach. Moving and cutting were treated separately. First, the machine moved forward until either trees in front blocked its path or a tree on the side was about to pass out of reach. Whichever happened first stopped the machine. All trees within reach were then cut before moving again. Thus, two questions were asked: how far is it to the next stopping point? And once stopped, how many trees are within reach?

As explained earlier, when trees are randomly scattered, the number of trees in any sample area is Poisson distributed and proportional to trees per acre. If this question was merely one of scanning the strip for the next tree, as it was for the rubber-tired machine, the answer would be straight forward. However, the shape of the tracked machine's felling area is different. Both the front and trailing edges are curved and the area occupied by the machine in the center of its felling area cannot contain trees.

To resolve this difficulty, random distributions of trees in strips were prepared, and plotted, and a template of the tracked feller-buncher's felling area was "moved" down each. When a tree either blocked the machine or was about to pass out of reach, the template was stopped, the distance traveled was measured, and the trees within reach were counted. From a series of these experiments we developed two equations. First, the distance between stopping points followed an exponential distribution with

the mean distance:

$$\mu_D = 14.68130e^{0.03813}$$

where: $e = 2.71828$,
 $S = \text{equilateral tree spacing} = (43,560/0.866T)^{1/2}$, and
 $T = \text{trees per acre.}$

Second, the number of trees found at each stopping point followed a Poisson distribution with the mean number of trees:

$$\mu_N = 1.78910 + 0.01340T$$

where: $T = \text{trees per acre.}$

At least one tree was cut at each stopping point.

Harvest Experiments

Feller-buncher simulations. Given the 12 stand combinations and the 3 harvesting models, we conducted a series of harvesting experiments. For all feller-buncher simulations, 10,000 trees were cut, and tree diameters, volumes, weights, distances, travel times, cutting times, and bouquet and bunch sizes were recorded. These data were then subjected to the various calculations and adjustments for the machine and system comparisons.

Several additional experiments were conducted on the rubber-tired machine. First, two different shear accumulator capacities were examined; 25 inches as a sum of diameter limit (same as the tracked limit) and 15 inches. Finally, we carried out harvests with optimum and nonoptimum strip widths and optimum and non-optimum bunch distance limits.

Skidding and chipping simulations. After each stand was felled and bunched the record of bunches was fed to the skidding and chipping simulator. Because bunch distances from the landing ranged from 0 to 660 feet and one skidder was usually too slow for the chipper, two grapple skidders were created to operate simultaneously on their own 10,000-tree set. Each set of trees was skidded and chipped in precisely the same order as felled. Although the two skidders interacted with each other and the chipper at the landing, no skidder interactions were allowed in the woods.

Machine availability and productivity calculations. Although each simulated harvest created a lot of data, we were mainly interested in the production and time requirements to either fell and bunch or skid and chip. Many frequency tables were used to check the conformity of system input and output. For each stand, machine, and system combination, the most important items were production in tons and time in hours. Their ratio, tons per hour, is a so-called ideal productivity and is the major statistic used in all comparisons.

Ideal productivity is defined as the maxi-

mum potential output given the operator skill levels implied by the machine speed data listed earlier. Yet because the simulator did not account for mechanical breakdowns or rest periods, these maximums were also adjusted by the following factors to yield a "realistic" productivity.

	<u>Percent of ideal productivity</u>
Tracked Feller-Buncher	60 percent
Rubber-Tired Feller-Buncher	65 percent
Grapple Skidders	67 percent
Full Tree Chipper	80 percent

Results

Feller-Buncher Productivity Comparisons

Both feller-bunchers have 25-inch shear capacity. For stands averaging 6 inches in diameter, "ideal" production rates between the two machines were similar, although the tracked machine showed a slight advantage (5 percent) when basal area was 150 sq. ft. per acre. But if these ideal outputs are adjusted to the more "realistic" availabilities assumed in this study, the rubber-tired machine had a consistent advantage although again differences were small at any basal area (Table 4).

Table 4. Ideal machine and system productivity.

		Basal Area	
		(sq. ft. per acre)	
		60	150
Machine			
	(inches)	(green ton/hour)	
<u>Average DBH = 6 inches</u>			
TRACKED FB	25	31.0	34.4
RUB-TIR FB	25	31.1	32.8
RUB-TIR FB	15	27.8	29.4
SKDRS	--	37.3	37.7
SYSTEM	--	35.6	35.7
<u>Average DBH - 8 inches</u>			
TRACKED FB	25	49.8	58.2
RUB-TIR FB	25	54.3	57.6
RUB-TIR FB	15	48.8	51.8
SKDRS	--	53.0	53.2
SYSTEM	--	47.6	47.4
<u>Average DBH - 10 inches</u>			
TRACKED FB	25	68.5	84.0
RUB-TIR FB	25	87.6	93.2
RUB-TIR FB	15	80.8	85.1
SKDRS	--	63.5	67.0
SYSTEM	--	58.5	60.9

For stands averaging 8 inches in diameter, ideal production rates between the two machines showed larger differences. When basal area was 60 sq. ft. per acre, the rubber-tired machine had about a 9 percent advantage. But when basal area was 150 sq. ft. per acre, the tracked

machine's "ideal" productivity slightly exceeded that of the rubber-tired machine. After adjusting for availability, the rubber-tired feller-buncher was consistently more productive. However, margins decreased continuously from 18 to 7 percent as basal area increased from 60 to 150 sq. ft. per acre.

For stands averaging 10 inches in diameter, "ideal" production rates between machines showed the largest differences. When basal area was 60 sq. ft. per acre, the rubber-tired machine had a 28 percent advantage. And when basal area was 150 sq. ft. per acre, although differences were smaller, the rubber-tired machine was still 11 percent more productive. After adjusting "ideal" productivity to "realistic" levels, the rubber-tired machine was consistently more productive. It had a 39 percent advantage over the tracked machine when basal area was 60 sq. ft. per acre. But when basal area reached 150 sq. ft. per acre, its advantage declined to 20 percent.

Unequal shear capacity: the rubber-tired limit has been reduced to 15 inches. For stands averaging 6 inches in diameter, the tracked machine was consistently more productive than the rubber-tired machine. The margin was 10 percent with a basal area of 60 sq. ft. per acre, and it increased to 17 percent with a basal area of 150 sq. ft. per acre. After adjusting for the availability, the tracked machine is still more productive but differences are less than 8 percent (Table 4)

For stands averaging 8 inches in diameter, although the tracked machine was only slightly more productive than the rubber-tired one when basal area was 60 sq. ft., it was 12 percent more productive when basal area was 150 sq. ft. After adjusting for availability, the rubber-tired machine was slightly more productive at 60 sq. ft. and slightly less productive at 150 sq. ft.

For stands averaging 10 inches in diameter, the rubber-tired machine was more productive than the tracked machine at all basal areas, with an 18 percent advantage at 60 sq. ft. but only a 1 percent advantage at 150 sq. ft. After adjusting for availability, the rubber-tired machine was substantially more productive at all basal areas.

In general then, basal area has a greater effect on the productivity of the tracked machine than on the productivity of the rubber-tired machine. This is consistent with the assumption that the tracked machine has a fixed boom reach and fixed strip width for all stands. In contrast, the rubber-tired feller-buncher operator was allowed to optimize strip-width as stand density changed and was also allowed to choose an optimum distance limit while creating full size bunches.

System Productivity

In contrast to the previous comparisons,

both skidder output and chipper or overall system output are unaffected by basal area, regardless of feller-buncher type or shear capacity! In every case, system output was constrained only by tree diameter: larger trees mean higher system output, as one would expect (Table 4).

The Effect of Nonoptimum Strip Widths on Rubber-Tired Feller-Buncher Output.

Previous results showed rubber-tired output when strip width was three times the mean Y-coordinate difference between trees up the strip. To show the effect of nonoptimum strip width on productivity, four simulated harvests were conducted with strip width equal to the mean Y-coordinate difference. Thus, because

$$(W)(\mu_D) = 43,560/T$$

and if, as now assumed, $W = \mu_D$

$$\text{then } W_{\text{nonoptimum}} = (43,560/T)^{1/2}.$$

All four stands used in this nonoptimum simulation averaged 10 inches in diameter and basal areas ranged from 60 to 150 sq. ft. per acre. Shear capacities were 25 inches and the bunch distance limit was set to the previously established optimum. Strip widths for the four stands differed from the optimum strip widths as follows:

Basal Area (sq. ft. per acre)	Strip Width	
	Optimum	Nonoptimum
	------(Feet)-----	
60	41.74	24.10
90	35.79	20.67
120	31.11	17.96
150	27.97	16.15

Nonoptimum strip widths in this brief example reduced the rubber-tired feller-buncher's ideal output from 87.6 to 83.8 tons per hour when basal area was 60 sq ft per acre and from 93.2 to 91.0 when basal area was 150 sq. ft. per acre -- 4.2 and 2.4 percent, respectively. Trees felled per hour showed similar relative reductions. The impact on system costs would be less because feller-bunchers represent only a portion of total costs.

The Effect of Nonoptimum Bunch Distance Limits on Rubber-Tired Feller-Buncher Output.

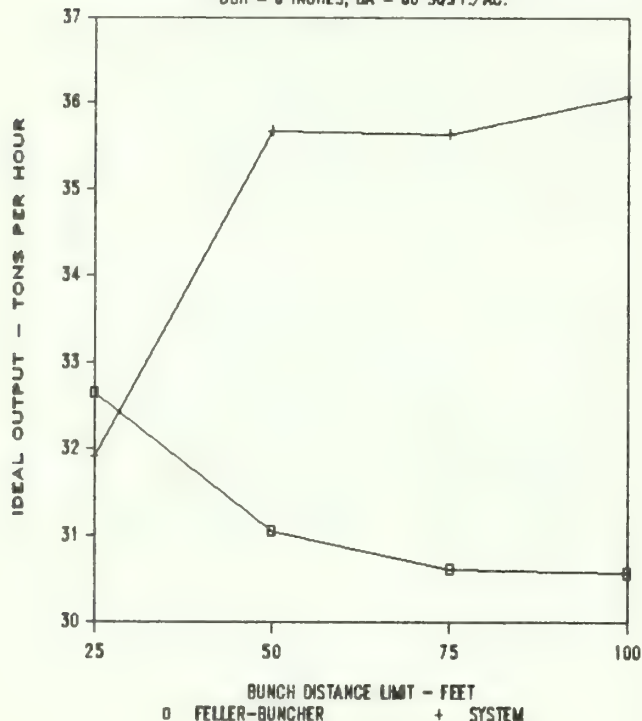
In previous simulations, bunch distance limits were used that traded declines in feller-buncher output against increased system output. The optimum bunch distance relationships for a 6 inch diameter stand and basal area of 60 sq. ft. are now shown for shear capacities of both 15 and 25 inches (Figure 1). Optimum strip widths were used in all cases.

Although rubber-tired feller-buncher output declined dramatically and then more gradually as the bunch distance limit increased, system out-

put leveled off after a very rapid increase. Note also, that although shear capacity affects feller-buncher output, it has almost no effect on system productivity; system output was almost identical once the optimum bunch distance limit was achieved or exceeded, regardless of shear capacity.

BUNCH DISTANCE LIMIT AFFECTS OUTPUT

DBH = 6 INCHES; BA = 60 SQ.FT./AC.



Traveling at least 50 feet back in these examples increased system output for the 25 inch shear about 13 percent compared to 25 feet (from 32 to 35.5 tons per hour). For a 15 inch shear system, output increased almost 17 percent (from 30 to 36 tons per hour). The effect on system cost depends on the number and cost of each machine but would probably be less than its effect on productivity.

Summary

Machine and system productivity of two feller-bunchers, each operating with two identical grapple skidders and a whole tree chipper, were compared for several diameter and basal area conditions, machine availabilities, shear capacities, and decision rules.

Equal and unequal feller-buncher shear capacities were compared as well as equal and unequal feller-buncher availabilities. When both shear capacity and availability were equal, the rubber-tired machine was more productive than the tracked machine in stands with low basal area or large trees. This result seemed intuitively correct because although the rubber-tired machine was allowed to adjust strip width to compensate for sparsely stocked stands, the

tracked machine, as modeled here, could not. Under these conditions, the tracked machine spent too much time traveling and not felling. When stocking was higher, the tracked machine could harvest many trees at one stopping point and was thereby able to surpass the rubber-tired machine.

When shear capacity was equal but the rubber-tired machine had greater availability (as it often does due to, among other things, a softer, easier ride), the rubber-tired machine was more productive than the tracked machine at all basal areas and diameters.

When the tracked machine had a larger shear capacity and was equally available, it was more productive than the rubber-tired machine for all stands averaging 6 and 8 inches in diameter. The rubber-tired machine was more productive for all stands averaging 10 inches. When the tracked machine had a larger shear but was less available, it was more productive for all 6 inch and 8 inch stands with basal areas equal to or greater than 120 sq. ft. per acre. The rubber-tired machine was more productive for all other diameter and basal area combinations. This last comparison is probably more pertinent to equipment presently on the market.

System productivity, however, is another matter. It must be emphasized that for the range of stands and assumptions examined here, neither feller-buncher significantly affected system output per hour. Only stand diameter affected system productivity. Diameter had the only effect on productivity because first, chipper output is almost exclusively a function of diameter. Thus, large trees mean high output. Second, although skidders were not permitted to interact with feller-bunchers in the woods, both feller-bunchers and skidders attempted to build capacity bunches to ensure that the chipper didn't wait for wood. Again, the main point is that final choice of a system based on one or the other feller-buncher, as modeled in this report, depends primarily on relative machine costs.

This report also suggests how rubber-tired fixed shear feller-buncher operators may increase system productivity and lower cost by choosing optimum harvest strip widths as well as optimum bunch distance limits. These two opportunities applied only to the rubber-tired machine in this study because we assumed that only this machine could vary strip width or could travel back if necessary to drop bouquets on incomplete bunches. Tracked feller-bunchers with rotating booms are not usually operated this way and were not permitted to do so here.

If optimum strip widths are adopted, rubber-tired feller-buncher productivity can be increased up to 4 percent. While these are only modest gains, adopting an optimum bunch distance limit can have a dramatic effect on productivity. For machines with the large shear, traveling back to create a capacity bunch increased system productivity as much as 13 percent. For

machines with the small shear, the corresponding improvement in system productivity was 17 percent. These optimizing rules for the rubber-tired machine were followed for all system comparisons.

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PRODUCT QUALITY AND CONSUMER ACCEPTANCE OF WOOD
PRODUCTS FROM INSECT-DAMAGED BALSAM FIR

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Studies concerning the product quality and acceptance of balsam fir lumber in the marketplace are summarized. Balsam fir is apparently well suited for the production of stud-size dimension lumber. Misconceptions concerning the physical appearance of balsam fir lumber need to be overcome. In addition, according to retail lumber dealers growth in the market for balsam fir as a single species is hindered by a lack of reliable suppliers producing consistently high quality lumber.

Introduction

Product quality, as it relates to solid wood products in the absence of structural considerations, is most often simply in the eye of the beholder. We are all familiar with many characteristics of wood which in certain circumstances would be considered defects, however, in other situations they are considered attributes. As examples of this, we find the following products in our marketplace selling many times at premium prices; pecky cypress, wormy chestnut, knotty pine, and birdseye maple to name only a few.

Unfortunately, I have not (as of this writing) discovered wormy balsam fir selling at a premium in the marketplace. However, there are several entrepreneurs producing paneling and other decorative products from insect-damaged softwood timber. The blue stained southern and western pines, results of bark beetle attacks, have found a small niche in the marketplace and are sometimes marketed with such names as blue pine or homestead pine. These are typically processed into narrow tongue-and-groove strips for interior paneling. There is no reason to presume that budworm-damaged balsam fir could not be manufactured into similar decorative products.

While such decorative products can provide high value outlets for insect-damaged timber, the volumes of decorative products that our markets are able to absorb is small in relation to the volumes of insect-damaged timber. For balsam fir, its primary market as a solid wood product is dimension lumber. It is most commonly graded and marketed as part of a species group but can also be graded and

marketed as an individual species. An example of this is provided by the National Lumber Grades Authority's standard grading rules for Canadian lumber (NLGA 1978). Under these rules balsam fir may be marketed under the following four commercial names or species groups, each with a different identification stamp:

Commercial name	Identification stamp
Balsam fir	B Fir (N)
Alpine fir	Alpine Fir (N)
Spruce-pine-fir	S-P-F
Northern species	North Species

According to NLGA rules, lumber marketed as balsam fir under the identification stamp of B Fir (N) would clearly be balsam fir lumber. However, shipments of lumber marketed under the other commercial names and identification stamps also can contain balsam fir, in part or in total, though it is not required that balsam fir make up any part of a shipment under any of these three stamps. Similar parallels can be drawn from the grading rules of the Northern Hardwood and Pine Manufacturers Association (NHPMA 1979) and the Northeastern Lumber Manufacturers Association (NELMA 1980).

Standard grading rules of the NHPMA allow balsam fir dimension lumber to be graded and sold in three categories: balsam fir, eastern softwoods, and eastern woods. The NELMA grading rules allow balsam fir dimension lumber to be graded and sold in four categories: balsam fir, eastern spruce and balsam fir, eastern softwoods, and eastern woods.

Product Quality of Balsam Fir Dimension Lumber

To compare grade yields of living balsam fir to yields from budworm-killed trees, studies were conducted with 100-inch bolts at a commercial sawmill in northern Minnesota (Govett et al. 1983). These bolts were harvested from eight test plots where more than 400 severely weakened balsam fir trees had been individually tagged for observation in the spring and early summer of 1979. As was expected, the majority of these test trees died during the following 2-year period. Each year, monthly observations of each test tree were conducted from early spring through late fall to determine the time of tree death. Observable characteristics followed the pattern reported by Belyea (1952); cambial discoloration represented the point of death. The observation procedure is described by Govett (1982).

In the first grade yield study, conducted in the early fall of 1980, bolts were sawn from 18 healthy trees and from 32 trees that died during the previous fall. The second study, conducted in the summer of 1981, examined the potential product quality of lumber sawn from the following four categories:

1. Trees stressed by considerable budworm defoliation but not yet dead (21 trees).

2. Trees standing dead approximately 6 months or less, having died over the preceding winter or in spring or early summer (24 trees).

3. Trees standing dead about 1 year, having died in summer or early fall of the previous year (33 trees).

4. Trees standing dead about 18 months, having died over the winter of 1979-80 (21 trees).

All 100-inch bolts in each study were sawn at the same commercial mill; a circular headrig (1/4-inch kerf) and a single-arbor bull edger were used. The sawyers were instructed to maximize production of 2- by 4-inch and 2- by 6-inch dimension lumber with a minimum of 1-inch boards sawn. Sawyers were instructed not to heavily slab bolts to remove decay since enhancement of grade yields by such a practice would be at the expense of volume yields.

All lumber sawn for each grade yield study was graded as 8-foot lengths after air drying and surfacing by the Chief Inspector of the Northern Hardwood and Pine Manufacturers Association. All 2- by 4-inch lumber was graded under Light Framing, Structural Light Framing, and Stud grading rules; all 2- by 6-inch lumber was graded as Structural Joists and Planks. A record was kept of the primary defect preventing each piece of lumber from receiving a higher grade to ensure that increasing grade downfall after death was attributable primarily to factors associated with budworm-caused mortality rather than by other factors or by chance.

The aggregate grade yields of lumber sawn in each tree category in both studies are shown in Table 1. The larger percentages of lower grade lumber associated with increasing time after death are almost wholly a result of the progression of deterioration in the dead standing tree. Less than 5 percent of the lumber produced from dead trees was degraded because of insect holes. More than half of all dimension lumber sawn from trees dead 1 year or longer graded lower than No. 2 or Standard due to the onset and progression of decay in the dead standing tree.

Table 1. Lumber grade yield of 2- by 6-inch, 2- by 4-inch, and 1-inch balsam fir, by tree class and grade^a (Govett et al. 1983).

Size and grade	<u>1980 lumber yield</u>		<u>1981 lumber yield</u>				Percent of total lumber produced in size
	Healthy	Dead 1 year	Stressed or dying	Dead 1/2 year or less	Dead 1 year	Dead 1-1/2 years	
<u>Percent</u>							
2- by 6-inch (38- by 140-mm) dimension lumber							
Select structural	16.4	1.4	23.5	6.3	7.7	0.0	37.3
No. 1	0.0	0.0	5.9	5.1	0.0	0.0	
No. 2	29.1	4.3	17.7	15.2	19.2	0.0	
No. 3	41.8	44.3	23.5	40.5	34.6	42.6	
Economy	12.7	50.0	29.4	32.9	38.5	57.4	
2- by 4-inch (38- by 89-mm) dimension lumber							
Construction	42.8	2.5	44.4	16.2	5.0	2.9	57.9
Standard	27.3	10.0	15.2	6.8	10.6	2.9	
Utility	20.8	63.3	22.2	59.0	52.5	66.6	
Economy	9.1	24.2	18.2	18.0	31.9	27.6	
1-inch (19-mm) boards							
Nos. 1 & 2 Common	57.1	0.0	14.3	9.1	5.2	0.0	4.8
No. 3 Common	28.6	0.0	71.4	0.0	10.5	0.0	
Nos. 4 & 5 Common	14.3	100.0	14.3	90.9	84.3	100.0	

^aLumber grades are S-dry for 8-foot lengths. Grade downfall in 2- by 6-inch lumber from the healthy tree category is primarily due to excess wane allowed in sawing and heart rot.

Table 2 places all dimension lumber into three grade categories: Standard & Btr or No. 2 & Btr, Utility & Btr or No. 3 & Btr or Stud, and Economy. It points out the relatively high yields of Utility or No. 3 & Btr or Stud, compared with Standard & Btr or No. 2 & Btr. If dead standing balsam fir is to be used in the production of dimension lumber, it is probably better suited to producing Utility or No. 3 & Btr or Stud.

In sawing dead balsam fir, some volume losses might be expected due to breakage in the mill; this problem, however, did not have a significant effect on the volume yields in this study.

Govett et al. (1983) concluded that balsam fir bolts apparently are well suited to the production of common stud sizes of dimension lumber. Lumber sawn from bolts of both healthy and stressed trees exhibited both straightness and a good general appearance. The relatively rapid onset of decay in dead standing balsam fir in Minnesota caused a significant downfall in lumber grade soon after tree death, from Standard & Btr or No. 2 & Btr to Utility or No. 3. Progression of decay with increasing time after death caused greater downfall of lumber to the Economy grades.

A mill's decision to saw dead balsam fir may hinge primarily on the type of market in which the lumber will be sold. Mills predominantly selling Stud, No. 3, or Utility & Btr. grades should experience less adverse effects when sawing recently killed trees than mills producing lumber for sale in grades of

Standard & Btr. or No. 2 & Btr. The latter mills may experience significant grade yield falldown by sawing trees standing dead for even a few months in areas where decay rates for standing dead timber are similar to those in northern Minnesota.

Consumer Acceptance of Balsam Fir Dimension Lumber

Carpenter and Quinney (1965) describe the consumer acceptance and sometimes preference for balsam fir lumber in northern Minnesota, where more than 75 percent of the retail lumberyards sampled carried balsam fir lumber. However, only 8 percent of the retail lumberyards in the Twin Cities area handled balsam fir lumber. The reasons for these differences were thought to be low production outputs, relatively high prices, and the lack of reliable suppliers. In the northern area, most of the yards obtained their stock of balsam fir lumber directly from nearby mills or from captive mills. In yards in both areas that carried balsam fir, the species apparently was widely accepted and in many instances preferred.

Carpenter and Quinney (1965) identified four primary requirements for the increased use of balsam fir lumber. The two most important factors are that the material should be kiln dried and that the price should be slightly below that of competing western species. Appearance was stressed as many sellers noted that balsam fir's light color, straight grain, and small knots enhance its salability. The fourth factor was reliability of supply. Once customers have accepted the species, the yards must be assured a dependable supply of lumber manufactured in a consistent manner.

Table 2. Dimension lumber grade yields for 2- by 4-inch (38- by 89-mm) and 2- by 6-inch (38- by 140-mm) material combined by tree category (Govett et al. 1983)

Tree category	Standard & Btr or No. 2 & Btr	Utility & Btr or No. 3 & Btr or Stud	Economy
<hr/>			
		<u>Percent</u>	
		<u>1980 Study</u>	
Healthy	57.8	89.3	10.7
Dead 1 year	9.1	63.5	36.5
		<u>1981 Study</u>	
Stressed or dying	56.2	79.5	20.5
Dead 1/2 year or less	24.4	73.7	26.3
Dead 1 year	17.8	68.3	31.7
Dead 1-1/2 years	3.5	59.3	40.7

Ostaff and Petro (1977) echoed the need to kiln dry balsam fir, particularly lumber cut from budworm-killed balsam fir. They cite instances of shipments that were rejected because the lumber contained live larvae of the sawyer beetle. This was particularly damaging in large export sales but also damaging in domestic markets. Consumers tend to respond negatively to the sight of live insects emerging from the wood in their homes. Kiln drying usually is sufficient to kill insect larvae and prevent such problems.

A more recent survey concerning the marketing of balsam fir dimension lumber was conducted by Govett and Sinclair (1984). Their findings are based on responses from 77 retail lumberyards located in the north-central and northeastern United States. The following shows

the average market share for balsam fir sold as a single species; however, a portion of the market share for spruce-pine-fir no doubt includes some balsam fir.

Species or group	Average percentage of total
	softwood lumber sales
Spruce-pine-fir	36.8
Douglas-fir and hem-fir	30.4
Eastern spruce	7.7
Other west coast species	7.5
Southern pine	7.5
Northern pine	6.5
Other softwoods	1.9
Balsam fir	1.7
Total	100.0%

Table 3. Attitudes of retail lumber dealers concerning statements related to lumber or lumber customers, by percentage of respondents agreeing or disagreeing with each statement (Govett and Sinclair 1984).

Statement	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
	<u>Percent</u>				
The quality of softwood dimension lumber produced on the west coast is highly superior to lumber produced from northern mills.	2.6	15.8	18.4	42.1	21.1
The quality of southern pine dimension lumber is highly superior to lumber produced from northern mills.	11.0	42.5	27.4	12.3	6.8
It is very difficult to obtain a steady supply of dimension lumber produced by local northern mills.	3.9	13.2	32.9	38.2	11.8
Most customers have a very strong preference for dimension lumber produced on the west coast or southern United States.	6.6	32.9	12.8	36.8	7.9
The quality of dimension lumber produced by local northern mills is very inconsistent.	1.4	12.2	32.4	40.5	13.5
Most customers have a very strong preference for lumber that is kiln dried rather than air dried.	1.3	11.8	7.9	43.5	35.5
Do-it-yourself or walk-in customers purchase 2- by 4-inch studs almost totally on the basis of general appearance, straightness, and low price.	0.0	0.0	1.3	40.8	57.9
Very often 2- by 4-inch balsam fir studs have large or loose knots and tend to warp and twist to a large degree.	4.3	15.7	58.6	15.7	5.7

Problems identified by Carpenter and Quinney (1965) were still prevalent in the results of the Govett and Sinclair (1984) study. For example, the following summary shows that only 45 percent of the respondents reported that balsam fir was currently available from one or more suppliers of dimension lumber:

<u>Species or group</u>	<u>Average number of suppliers</u>	<u>Percentage of yards reporting species or group available from one or more suppliers</u>
Spruce-pine-fir	4.4	92
Eastern spruce	3.3	70
Balsam fir	1.7	45
Northern pine	1.5	62

Table 3 shows that 50 percent of responding retail lumber dealers either agreed or strongly agreed that it is difficult to obtain a steady supply of dimension lumber from local sawmills. However, lack of availability may not be true for all areas. Nearly all of the respondents agreed that walk-in customers purchase 2- by 4-inch studs almost totally on the basis of general appearance, straightness, and low price. Unfortunately, approximately 20 percent of the respondents believe that balsam fir studs often have large, loose knots and tend to warp and twist. This last perception is largely incorrect and evidently due to a lack of familiarity with the species.

Table 4 ranks dimension lumber of five species or species groups according to perceptions of retail lumber dealers (Govett and Sinclair 1984). Douglas-fir had the highest average rank and southern pine the lowest. Table 5 ranks the importance of characteristics of 2- by 4-inch studs to large-order customers (Govett and Sinclair 1984). Being straight and kiln dried are considered the most important characteristics.

Summary

Lumber grade yield studies have shown healthy balsam fir can produce relatively good yields of high quality stud-size lumber. Grade yields of budworm-killed timber drop rapidly after tree death with more than half of the dimension lumber volume being lower than No. 2 or Standard only one year after tree death.

Balsam fir lumber is readily accepted, even preferred, in areas where the species is familiar to retail lumber dealers. Problems with reliability of supply and inconsistent quality hinder wider market acceptance. In addition, some retail lumber dealers have misconceptions concerning the appearance of balsam fir studs.

Table 4. Perceptions of retail lumber dealers on the quality of studs produced from various species or groups, by percentage of respondents for each ranking from best quality (1) to worst quality (5) (Govett and Sinclair 1984).

<u>Species or group</u>	<u>Ranking used by respondents^a</u>					<u>Average rank</u>
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	
Douglas-fir	68.4	14.0	10.6	3.5	3.5	1.6
Eastern spruce	19.6	33.9	16.1	14.3	16.1	2.7
Balsam fir	9.2	22.2	24.1	24.1	20.4	3.2
Northern pine	7.3	20.0	32.7	23.6	16.4	3.2
Southern pine	0	14.8	14.8	27.8	42.6	3.9

^aColumns and rows do not total 100 because several respondents assigned less than five ranks.

Table 5. Importance of various characteristics of studs to large-order customers of retail lumber dealers, by percentage of respondents who ranked characteristics from unimportant (1) to very important (5) (Govett and Sinclair 1984).

Characteristics	Ranking used by respondents					Average rank
	1	2	3	4	5	
Straightness	1.4	1.4	13.9	25.0	58.3	4.4
Kiln dried versus air dried	4.2	18.3	21.9	16.2	39.4	3.7
Low price	1.4	7.1	50.0	18.6	22.9	3.5
General appearance	2.7	4.2	45.8	30.6	16.7	3.5
Absence of wane	4.3	10.0	40.0	27.1	18.6	3.4
Absence of stain and decay	4.2	19.7	33.9	22.5	19.7	3.3
Absence of insect holes	7.0	22.5	25.4	28.2	16.9	3.2
Strength	9.7	26.4	37.5	18.1	8.3	2.9
Stud of a western species	20.0	32.9	17.1	17.1	12.9	2.7

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Introduction

Spruce budworm outbreaks have been known to occur in eastern North America for at least 300 years. Blais, who has reviewed this period (1983), has concluded that outbreaks are becoming longer, more frequent, more severe, and envelop substantially larger acreages.

In fact, the first 200 years of known budworm history are characterized by regional outbreaks that did not spread to adjacent forests and were essentially local in character. Some of these outbreaks were quite severe and caused tree mortality, but consecutive outbreaks in a given region were usually separated by at least 60 years.

Toward the end of the 18th century, a first break was observed in this pattern with the occurrence of an outbreak which started around 1760 and covered most of southern Quebec, Maine and New Brunswick (Blais, 1968). For the most part, the 19th century was characterized by local outbreaks, but epidemic activity was observed in the southern part of the range (southern Quebec, Maine and New Brunswick).

The major break in the pattern occurred with the 20th century. The first 60 to 70 years produced three major outbreaks each one more severe and more widespread than the last. The 1910-23 epidemic which occupied some 10 millions hectares of forest in eastern Canada was the first to gain access to the Gaspé peninsula and the Ottawa River watershed.

With 25 millions hectares, the 1940-58 outbreak more than doubled the size of the previous epidemic while new regions such as Quebec North Shore suffered tree mortality for the first time. Following its general collapse, sizeable residual outbreaks kept going particularly in central New Brunswick and north eastern Maine --- a phenomenon observed for the first time.

Between 1964 and 1967 a new outbreak started which proved to be the most widespread ever recorded with some 55 millions hectares in eastern Canada only. This outbreak which is still underway occupied at one time or another most of the range of balsam fir and marked the shortest interval between two consecutive outbreaks ever recorded. Sizeable tree mortality occurred for the first time in many regions previously considered less vulnerable, New Foundland, Cape Breton Island, Anticosti Island among them.

Causes of Outbreaks

Review of Past Concepts

For a long time, spruce budworm outbreaks were associated with the dynamics of the classic spruce-fir forest. This school of thought prevailed for a long time and strongly influenced budworm management programs in the 1960's. Blais (1952) pointed out the role of staminate flowers of fir on the growth and development of budworm larvae and in 1960 the same author proposed that spruce budworm outbreaks were to be considered as one element leading to the climax of natural fir associations. Mott (1963) summarized these thoughts when he stated that large tracts of mature spruce-fir forest where balsam fir is the dominant species were the best conditions leading to the initiation of an outbreak. Although particular forest conditions were a must, the key factor that really triggered an outbreak was climate. Among others, (Wellington (1952), and Greenbank (1963), helped establish the concept that outbreaks were preceded by 3 to 5 consecutive pre-summer droughts and above normal temperatures.

In short, spruce budworm outbreaks were clearly associated with the dynamics of boreal spruce-fir ecosystems. Given the right climatic conditions an outbreak would develop in mature and overmature stands thus killing the trees and hastening the return of a climax forest association.

The first challenge to this concept came with the current outbreak in Quebec when it was observed that it did not originate in the spruce-fir forest. Hardy et al (1983) analyzed the vegetation from seven locations in Quebec where the outbreak gained its initial momentum between 1967 and 1972. Their findings showed the same regular pattern everywhere. Although fir and spruce were the most abundant single species, they were far out numbered by the other species present, some of which, e.g. sugar maple, yellow birch, and white pine etc., occurred almost everywhere (Table 1). On the other hand, the spruce-fir components of the stands usually belonged to the 30 - 50 age classes, rarely showing signs of over-maturity.

The vegetation analyses were extended to include other parts of the spruce budworm range including Manitoba, Ontario, New Brunswick and Maine. The same findings were reported, and the young age of the host-trees was again observed while the forests associated with the epicenters were either northern hardwood or a transition type, fir-yellow birch.

Table 1. Relative Abundance of the Principal Tree Species Found in the Epicenters.

X: abundant species .: presence 1: Host species
2: Meridional species 3: Other species *: Pioneer species

Tree Species	Manitoba	Ontario										Quebec					Nouveau-Brunswick					Maine	
	Spruce Wood	Burchell Lake	Chapleau	Cobden I	Cobden II	Cobden III	Cobden IV	Arnprior	Low	Lac Dumont	Lac Duval	La Malbaie	Pohenegamook	Perce	Port-Daniel	Quebec Sud	St-Jacques	Lac Madawaska	Chatham	Nashwaak	Lac Lambert	Oxbow	Fish River Lake
1 Abies balsamea		x	x	x	x	x	.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
1 Picea glauca	x	.	x	.	x	x	.	x	.	x	.	x	x	.	x	.	.	.	.	.	.	.	.
1 Picea mariana		x	x	x	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
1 Picea rubens		.	.	.	.	.	.	.	.	.	.	x	.	x	x	.	x	x	x	x	x	x	x
2*Acer rubrum		.	.	.	x	x	x	.	x	.	x	.	x	x	x	x	.	.	.	x	.	x	.
2*Acer pensylvanicum		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
2 Acer saccharum		.	.	.	x	x	.	x	x	x	.	.	x	x	.	x	.	.	.	.	.	.	.
2 Betula alleghaniensis		.	.	.	.	.	.	.	x	.	.	.	x	x	x	x	.	.	x	.	.	.	.
2 Fagus grandifolia		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	x
2 Fraxinus americana		.	.	.	x	.	x	x	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
2 Ostrya virginiana		.	.	.	x	x	x	.	x	.	.	.	.	.	.	.	.	.	.	.	.	.	.
2 Pinus strobus		.	.	.	x	x	.	x	.	.	x	.	.	.	.	.	.	.	.	.	.	.	.
2*Quercus macrocarpa	x	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
2*Quercus rubra	.	.	.	.	x	.	x	.	.	.	x	.	.	.	.	.	.	.	.	.	.	.	.
2 Tilia americana		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
2 Tsuga canadensis		.	.	.	.	.	.	.	x	.	.	.	.	.	.	.	.	.	.	.	.	.	.
2 Ulmus rubra		.	.	.	.	.	x	x	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
3*Acer spicatum		.	.	.	.	.	.	.	.	.	.	.	.	.	.	x	.	.	.	.	.	.	.
3*Betula papyrifera	.	x	x	.	x	x	x	x	x	x	x	x	x	x	x	x	.	.	.	.	.	x	.
3*Populus tremuloides	x	x	x	.	x	.	x	x	x	x	.	x	.	.	.	.	.	.	.	.	.	.	.
3*Populus sp.		.	.	.	x	x	.	x	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
3*Prunus sp.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
3Thuja occidentalis		x	.	x	.	.	x	x	.	.	.	.	x	.	.	.	.	x	.	.	x	.	.

The New Budworm

Tothill (1922) and Bailey (1924) were the first to hint at the changing status of the budworm. Tothill noted that in less than a century the budworm changed from an innocuous insect to a major pest, while Bailey believed that these changes had been brought about by the removal of white pine from parts of Maine, New Brunswick and Quebec and its replacement by balsam fir.

Like any other living organism, the spruce budworm must satisfy some specific physical and biological requirements in order to survive. When both physical and biological (food) requirements are met in the same geographical area, insect outbreak conditions can occur since its needs are entirely fulfilled (Eidman, 1949 in Dajoz, 1980). Unless a third factor becomes involved (pathogens, predators, etc.) outbreaks could become chronic in an area where food and physical requirements are met.

Taking these considerations into account and the bioclimatic zonation concept formulated by Cook (1929), Bergevin (1984) attempted to determine where the budworm physical requirements are best met.

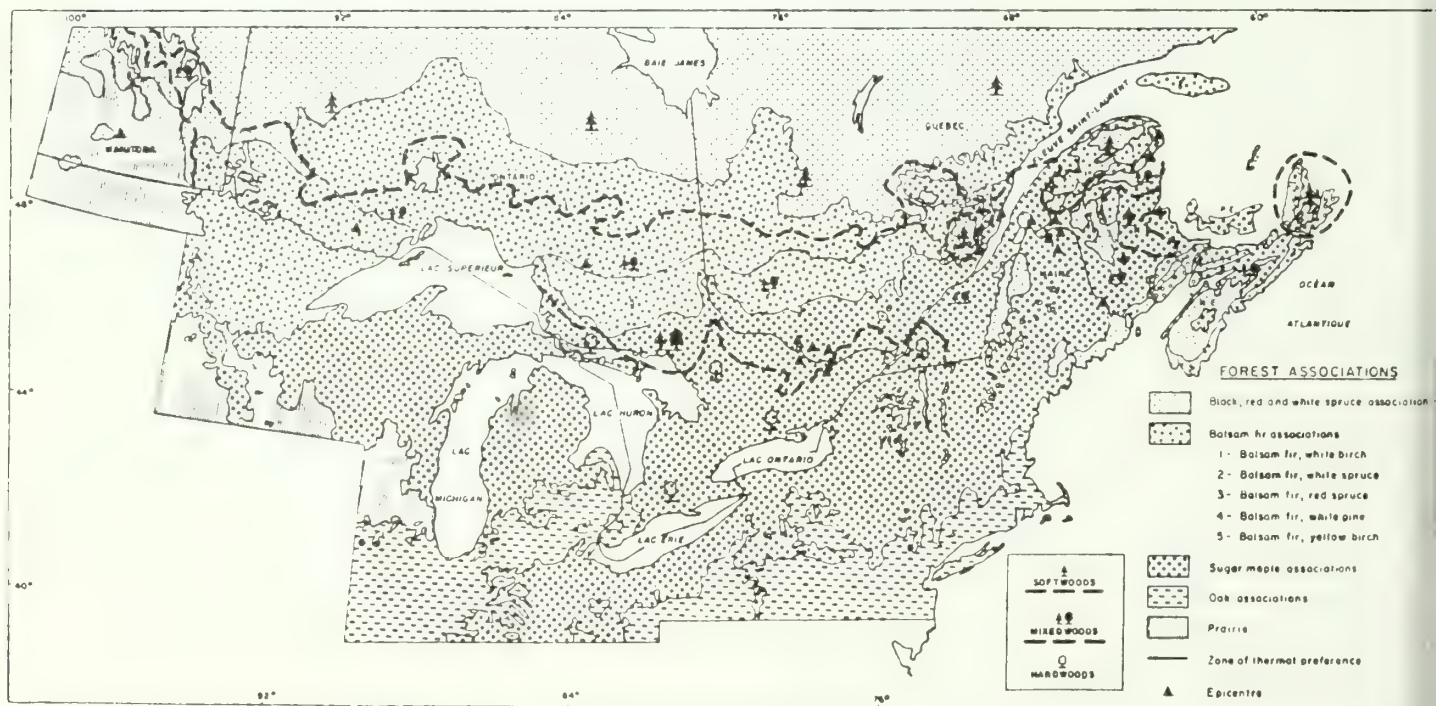
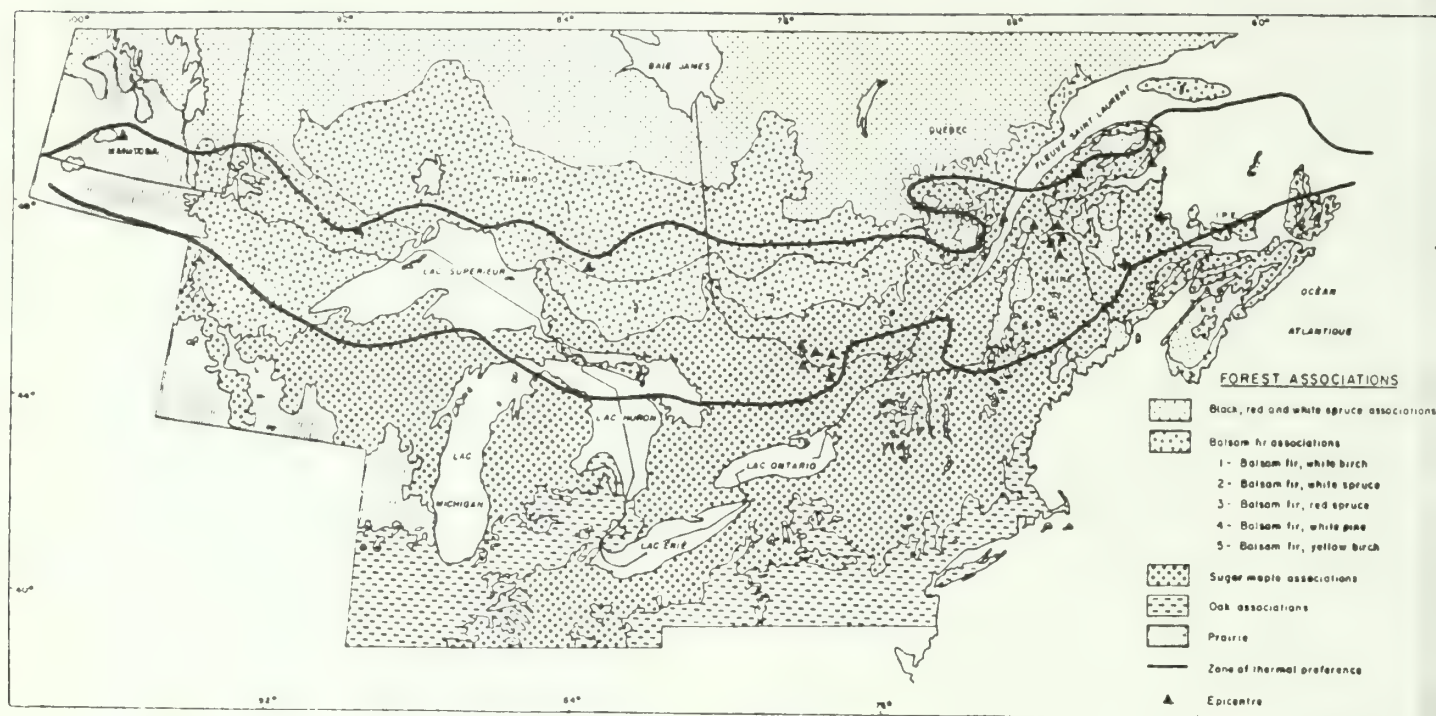
The mean summer and annual temperatures were analyzed using meteorological normals of 30 years for every epicenter recorded from Maine and New Brunswick to Manitoba. The results, incorporated in the summer and annual isotherms, defined a corridor which transected Maine, eastern Canada and the adjacent states in a east-west pattern. When superimposed over a forest association map, (Figure 1) this corridor included all epicenters; and the northern component of the maple association or a common northern variation, yellow birch-fir, not the climax spruce-fir boreal forest, dominates the corridor. This non host type which dominates the corridor corresponds to the zone of normal abundance for budworm according to Cook and should, by definition, counteract outbreak activity because of its biological resilience (absence of food, plus predation). However, changes in forest composition were observed everywhere, spruce and fir being the single most abundant species in most areas.

Invasion of the corridor by spruce and fir is a recent phenomenon related to man's influence on the forest ecosystem. Blais (1983) suggested that fire protection, clear-cut logging, use of pesticides against budworm favoring spruce-fir stands as well as abandonment of marginal farm lands have all contributed to favor an abundant regeneration of spruce and fir. The budworm was formerly forced to wait for specific climatic conditions to take advantage of the plentiful food source located outside the corridor, causing sporadic and local outbreaks. Now both can be secured most of the time from within the corridor thus explaining the changing character of the outbreaks.

The dramatic changes that took place in the eastern forest are best illustrated by a number of recent articles dealing with forest composition or forest vulnerability of the spruce budworm. Gaudet (1979) pointed to the abundance of white spruce on Prince Edward Island, a species that displaced the normal components of the Acadian forest region (Rowe, 1972). Reporting on Canada's forest inventory, Bonner (1982) produced a type map which showed that most of the northern hardwood regions had now become a mixedwood type (Figure 2). More significantly, the Blais and Archambault (1982) budworm vulnerability rating for Quebec's forests to the spruce budworm showed the St. Lawrence valley forests as the most vulnerable -- these forests are normally northern hardwood associations. Likewise Mac Lean's (1982) vulnerability ratings for the forests of New Brunswick and Nova Scotia exhibit a similar pattern, with high ratings associated with northern hardwood transition types.

Conclusion

The spruce budworm has adapted very well to its changing environment. From an almost innocuous insect, the budworm became, in less than a century, the most injurious forest pest of the northeast. Since this change can be related to changes in forest composition, the wisdom of our current forest management policies can be questioned. The current harvesting and reforestation practices increase the spruce and fir content of the meridional forest and this trend should be altered. The budworm's dynamic reaction to the transition types thus created not only affects the meridional forest where the problem originated, but impacts the boreal forest as well since the corridor can always be counted on as a reliable source of infestation for the adjacent climax spruce-fir forests. Future trends will depend on forest management policies in our respective countries. Although it may be a legitimate objective, from the economic viewpoint, to produce more spruce and fir, it would be ecologically and maybe economically more rewarding to avoid destabilizing the natural equilibrium of the major forest associations capable of supporting budworm.



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Abstract.--Measurements of cambial electrical resistance provide a rapid, simple and quantitative means to estimate growth potentials that can help assign risks to sites producing fir and spruce wood. Measurements of internal electrical resistance help refine estimates of risk by giving an indication of decay potential that affects wood quality.

Electrical Method Developed To Detect Wood Decay

The design of a pulsed electric-current meter to measure the resistivity of tree tissues was proposed in 1972 (Skutt, Shigo, and Lessard 1972). The concept was based on two principles: (1) water and inorganic ions accumulate in wood becoming decayed in living trees (Good, Murray, and Dale 1955, Ellis 1959, Shigo and Sharon 1970, Shortle and Shigo 1973), and (2) resistivity of a solution decreases with increasing ion content (Siggia 1968). If temperature is constant, asymptotic or normalized, then the water and ion content of tissues should determine the degree of resistance to a pulsed electric current. The relationship of resistivity to progressive stages of decay in trees was shown to be related primarily to increasing water and potassium ion in the discolored and decaying wood (Tattar, Shigo, and Chase 1972). It has been shown recently that in whiterot systems, which are most common in living trees, early ionization is due to potassium ions; but in brownrot systems, which are more common in butt rots of conifers and in utility poles, early ionization is due to hydrogen ions (Shortle 1982). However, whether in trees or wood products, whether whiterot or brownrot, accumulation of water and ions in tissues is the first in a series of progressive steps leading to wood decay. This ionization step can be detected by a pulsed electric-current meter equipped with proper electrodes.

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2/ Portions of the research discussed here were supported by CANUSA.

Electrical Method Applied to Cambial Zone

Potassium ions accumulate in plant meristems (Meyer, Anderson, and Böhning 1960). Therefore, it seemed possible that the same electrical method used to detect decaying wood also might be useful to observe variations in cambial activity, which in turn affects the periodic growth rate and thickness of phloem. A different electrode from that used in wood was attached to the meter, and the relationship of cambial electrical resistance, CER, to tree growth and vitality was first applied to oak (Wargo and Skutt 1975). Dominant trees had a lower CER than intermediate and suppressed trees. Trees with healthy crowns had a lower CER than those with severely defoliated crowns.

Similar methods for determining CER were applied to hybrid poplar and red maple (Shortle et al. 1977). Faster growing maples and poplars had lower CER values than slower growing maples and poplars regardless of size. This difference in CER values could be used for selecting crop trees during thinning operations in a sugar bush to increase growth rate of stems in the residual stand of sugar maple (Shortle et al. 1979).

CER values were related to phloem thickness as well as to periodic growth rates, which is as expected if vascular cambial activity was determining the degree of ionization to which the meter was responding (Carter and Blanchard 1978, Cole and Jensen 1980). Seasonal variations, not dependent on temperature, in maple, pine, and oak, were also consistent with CER varying in response to cambial activity (Davis, Shigo, and Weyrick 1979). The importance of variation in cambial thickness with season was not fully appreciated for several years, but was important in working out the controlling mechanisms for CER values (Blanchard, Shortle, and Davis 1983). Seasonal variations of CER, independent of temperature effects, limit the time for collecting data for site comparisons to the growing season during which the cambial zone is fully expanded. For our studies, mid-June to mid-August was the most useful period for measuring CER in Maine, New Hampshire, and Vermont.

The Method First Applied to Fir and Spruce

During the summer of 1978, several thousand trees were measured in cooperation with International Paper Company (Region VI) on continuous forest inventory plots. These plots (580 m²) were inventoried from mid-June to mid-August. After standard tree measurements had been made, the CER of each tree (> 12 cm dbh) was determined using a standard procedure (for details see Davis, Shortle, and Shigo 1980). Two measurements per tree on opposite faces took about 10 sec/tree or about 8 to 10 min/plot, depending on tree spacing, number of stems, and ease of walking between trees.

At the end of the summer, the results for all plots were combined for the seven major tree species observed (balsam fir, red spruce, yellow and paper birch, sugar and red maple, and beech) --150 to 500 observations per species. A mean CER was calculated for each species, and periodic growth rates over the 5-year-inventory period were compared in a two-class system (Table 1). Trees with CER values lower than the species mean were growing faster than those with CER values higher than the species mean. This was consistent with earlier studies done primarily in maple.

TABLE 1. Periodic growth rate for low and high electrical resistance classes for seven tree species.

Species	Growth rate (mm/yr) resistance class ^{a/}	
	Low ER	High ER
OVER ALL STEM DIAMETERS		
Balsam fir	2.6*	2.0
Red spruce	2.6*	1.4
Yellow birch	3.4*	2.2
Sugar maple	4.6*	2.6
Red maple	3.4*	1.8
Paper birch	2.4*	1.6
Beech	3.6*	2.2
WITHIN STEM DIAMETER CLASS		
Balsam fir	3.0*	2.2
Red spruce	2.6*	2.0
Yellow birch	3.4*	2.4
Sugar maple	4.4*	2.6
Red maple	3.6*	2.0
Paper birch	2.4*	2.0
Beech	3.4*	2.4

* Statistically significant $p < 0.05$.

^{a/} Low resistance class is one in which all trees have an electrical resistance less than the population mean resistance for that species, or less than the mean resistance for each 2.54-cm diameter class containing a minimum of 10 trees; high resistance class is one in which all trees have an electrical resistance greater than the population mean, or greater than the diameter class mean.

First Efforts Toward a Hazard Rating System

In 1979 under the sponsorship of the CANUSA Spruce Budworms Program, research was begun to develop a simple site-classification scheme using CER values to identify sites on which tree growth was poor (low growth potential). The stands on these sites were postulated to have a greater risk of mortality under outbreak conditions than stands or sites in which trees were growing substantially better (high growth potential). In addition to the high-risk sites, which have a low growth potential, and the low-risk sites, which have a high growth potential, there will be transitional sites, which are either declining or recovering. Monitoring CER over time would indicate the direction of change in growth potential.

During the summer of 1979, 10,000 trees were measured in 90 stands on 90 sites producing fir and spruce wood in Maine, New Hampshire, and Vermont. The predominant canopy was balsam fir (*Abies balsamea*) and red spruce (*Picea rubens*). Sampling was done along a transect with a 10-factor prism until at least 100 trees (8 to 10 points) were measured. Both outbreak and non-outbreak areas were included in the study with spruce budworm infestations ranging from none to severe. The mean electrical resistance for each stand/site was calculated for balsam fir or red spruce so the range and distribution of CER values for each species could be determined.

Mean CER values for balsam fir ranged from 9 to 18 k Ω on sites with moderate to heavy infestations; whereas red spruce values remained essentially constant at 7 to 13 k Ω . At the end of the growing season, 8 of the 90 stands were sampled for periodic growth rate to see how growth varied over the observed range of site values. In each stand, 10 canopy fir trees were selected at random and felled, and 5-cm-thick disks were taken at 20 cm and 140 cm above ground and at the base of the live crown. Air-dried disks were sanded and periodic growth was measured along the longest and shortest radii. Published results (Davis, Shortle, and Shigo 1980) are summarized in Table 2 along with results from studies in 1980 (Blanchard, Shortle, and Davis 1983).

Balsam fir growing on sites in which the CER of canopy trees averaged < 10 k Ω was adding an average of twice the increment of canopy trees on sites in which CER averaged > 12 k Ω (Table 2). Most sites in outbreak areas were of the latter category. If we assume that balsam fir growth before the outbreak was distributed similarly to non-outbreak areas, then growth was lost as < 10 k Ω sites progressively became > 12 k Ω sites, while sites already in > 12 k Ω status suffered the greatest mortality.

TABLE II. Periodic growth of trees on sites of high and low growth potential determined by cambial electrical resistance.

Year, species, and infestations	Mean periodic growth, mm/yr ^{a/}	
	Mean CER < 10 k Ω ^{b/}	Mean CER > 12 k Ω
1979, Fir, Non-outbreak	3.2	1.3
1979, Fir, Outbreak		1.5
1980-81, Fir, Non-Outbreak	2.9	1.4
1980-81, Fir, Outbreak		1.4
1982, Fir, Non-Outbreak	2.8	1.4
1982, Spruce, Non-Outbreak	2.4	1.3

^{a/} For details of 1979-81 data see Davis, Shortle, and Shigo 1980; Blanchard, Shortle, and Davis 1983; 1982 data was collected using 1980 plot sampling methods (3 fir sites < 10, 4 > 12; 4 spruce sites < 10, 2 > 12). Mean periodic growth represents 4 years prior to season of measurement.

^{b/} Mean CER of all canopy trees measured on each site, high growth potential < 10 k Ω , low growth potential > 12 k Ω .

To test the hypothesis of greater vulnerability for > 12 k Ω canopy trees than for < 10 k Ω canopy trees, acute stress in the form of girdling was applied to a small sample of such trees in the summer of 1982 (Shortle 1983). Balsam fir and red spruce trees were indexed for growth potential at the beginning of the growing season--high, CER < 10 k Ω ; low, CER > 12 k Ω --and half of each class was girdled. During the growing season, CER was measured and the condition of the bole and crown was observed every 2 to 4 weeks. Other studies had showed that rising CER preceded foliar symptom during tree mortality (Blanchard and Carter 1980).

CER increased in trees indexed as low growth potential before those indexed as high growth potential (Figure 1); and CER increased in fir before spruce. Bark beetle infestations followed the rise in CER in fir and spruce. Decreased CER followed infestations in fir as cambial tissues became infected. Foliar symptoms in fir and spruce lagged well behind changing CER and bark beetle infestations. Thus, CER indices of growth potential appeared to predict the expected sequence of damage due to stress. Fir of low growth potential (CER, > 12 k Ω) succumbed first followed by fir of high potential (CER, < 10 k Ω), red spruce of low potential, and finally spruce of high potential.

In summary, work to date indicates that measurements of cambial electrical resistance taken on a sufficient number of canopy trees during the growing season on sites producing fir and spruce wood may be a useful index of vulnerability to outbreak during periods of high stress. Empirical limits of < 10 k Ω for high growth potential sites and > 12 k Ω for low growth potential sites seemed to work well for balsam fir, and may be applicable to red spruce and other tree species. Trees of high growth potential at the beginning of the stress period are likely to shift to the low end of the normal range of growth, while those of low growth potential are more likely to die. Sites with trees in the transitional range of 10-12 k Ω may be declining in growth potential during a period of stress, or recovering from a period of stress. Thus, it is important to measure CER of trees over time to determine not only the level of growth potential, but the direction of change (decline, recovery, stable).

A Second Risk Factor--Internal Defect

The use of internal electrical resistance, IER, measurements to estimate the potential of living trees to internal decay is more complicated than the use of CER measurements because the target, columns of discolored and decayed wood, is not in a fixed position like the vascular cambium. Living trees may have no columns of discolored and decayed wood in the butt section where CER measurements are taken, or they may have columns only on one face. The distance of the column of decayed and decaying (often discolored) wood from the vascular cambium is highly variable, but very important to tree survival.

Studies on balsam fir during the 1981 growing season indicated that two general patterns existed in balsam fir (Shortle and Ostrofsky 1983). The IER increased to > 250 k Ω with increasing depth in most trees on some sites (Figure 2), a pattern consistent with sound healthy conifers. However, IER then decreased to < 100 k Ω , indicating early stages of column development in most fir of the 50 to 75 age classes we studied. The IER of red spruce in this age range generally stayed above 250 k Ω .

IER of most balsam fir on other sites remained below 100 k Ω , indicating that columns of decayed and decaying wood were spreading toward the vascular cambium (Figure 2). Wood of fir < 100 k Ω in positions where wood should be > 250 k Ω was interpreted as being in progressive stages of decay.

To test this hypothesis, decay tests were done in 1983 to determine the decay rate of wood from balsam fir with an IER of $> 250 \text{ k}\Omega$ (Type A, Figure 2), and with an IER $< 100 \text{ k}\Omega$ (Type B, C, D, Figure 2). Type B wood looked the same as A, but had become wet and ionized within the living tree, type C wood was ionized the same as B but visibly discolored, and type D wood was decayed by whiterot fungi in the living tree. When these four types of non-sapwood tissues from balsam fir were put in decay chambers with Haematostereum sanguinolentum, a decay pathogen of balsam fir, type B wood decayed faster than A and equivalent to C, and decay was most rapid in already decayed wood (Figure 3).

In a preliminary study done during the 1982 growing season, the IER at a depth of 4.5 cm was measured in 10 canopy trees on sites classified for growth potential by CER. Sites were classified as having a low decay potential if the IER of most trees was $> 250 \text{ k}\Omega$, or classified as high if most were $< 100 \text{ k}\Omega$. All spruce sites measured were rated as low, fir sites as half low, half high. Spruce from low decay potential sites had mostly type A non-sapwood in the butt section, fir some type A and type B, but little C and D. Fir sites rated as having a high decay potential had mostly type B, C, and D wood in the butt section. If these sites also had a low growth potential, mean CER > 12 , this makes such sites a very high risk to produce fir wood because internal decay is increasing as periodic growth is decreasing.

Each combination of growth potential determined by CER, and decay potential determined by IER, will have its own risks, problems, and remedies. The measurements are rapid, simple, and quantitative. The interpretation of the measurements are not simple, and require a thorough understanding of the complex growth and decay processes operating in trees. However, progress has been made toward developing an electronic monitoring system for periodic site evaluation over time to help forest managers see declining growth and increasing internal defect when there is still time to take effective action to minimize loss.

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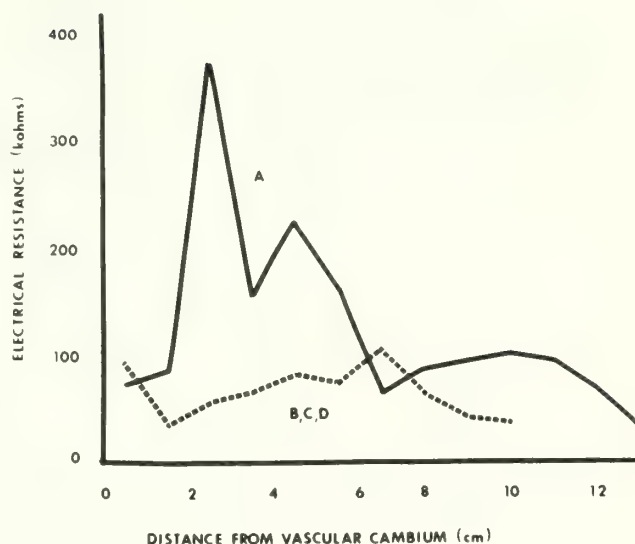


Fig. 2. Internal electrical resistance (IER) at 140 cm above ground with increasing depth from the vascular cambium. Solid line = tree from site of low decay potential with some type A wood (IER > 250 k Ω); broken line = tree with mostly type B, C, D wood (IER < 100 k Ω).

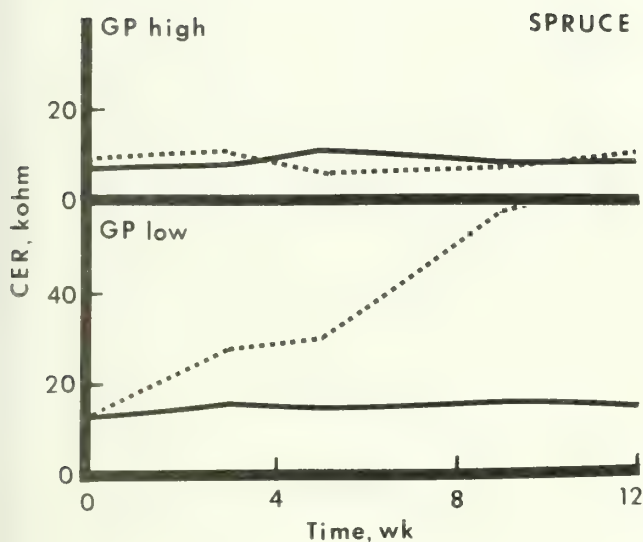


Fig. 1. Change in cambial electrical resistance during first 12 weeks after girdling of spruce trees of high growth potential (GP), CER < 10 k Ω , or low growth potential CER > 12 k Ω . Broken line = girdled trees; solid line nongirdled controls.

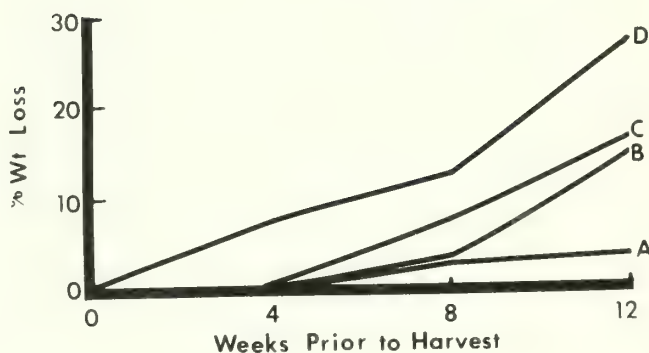


Fig. 3. Weight loss due to decay by *Haematostereum sanguinolentum*. A = nonsapwood with IER > 250 k Ω ; B = nonsapwood with IER < 100 k Ω that looks like A; C = wood like B but visibly discolored; D = wood like B but visibly decayed by a whiterot fungus.

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The annual defoliation of balsam fir trees by the spruce budworm produces different patterns of defoliation in different stands. These different histories produce different growth responses in the radial increment along the bole. As the reduced amount of current foliage remains on the tree to become the 1- and 2-year-old foliage, the volume growth in the upper portion of the bole is reduced. When the reduced foliage remains on the tree to become the foliage in the third or fourth age class, the volume increment in the lower bole is reduced. The results of three levels of protection and the resulting growth response are discussed. The effect of a single year of protection can be detected in increased growth response in the upper bole several years after application. Moderate protection, after defoliation, of nearly mature codominant balsam fir indicates that protection 3 out of 7 years can sustain the present level of bole volume growth without continued decline. Intensive protection after defoliation of younger dominant trees indicates that the volume growth along the whole bole can be brought back to earlier non-defoliated levels. The overall growth responses of balsam fir trees are related to the pattern of the defoliation history and the amount of foliage in the different age classes.

A major concern of forest managers is the growth response of trees in stands that are under stress. One of the most frequent stresses placed upon the spruce-fir forest in the Northeast is defoliation by the spruce budworm Choristoneura fumiferana (Clemens). Balsam fir, (Abies balsamea (L.) Mill), one of the major species in the spruce-fir forest, may retain its needles for 8 to 10 years. The budworm usually feeds on the current year's foliage, but occasionally feeds on the older foliage. Continued defoliation of the current foliage will have an influence on tree bole growth, and if severe enough may kill the tree.

A method of expressing bole growth at different locations along the bole has been presented by Duff and Nolan (1953). The radial increment at different locations along the bole, plotted over the age of cambium, has been widely used to show changes in bole growth of balsam fir caused by defoliation by the budworm (Mott et al. 1957) and also for western species (Williams 1967). These investigations have shown the growth response over the bole declines as the tree is defoliated by a single defoliation pattern. Work on Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) has shown how defoliated trees decline in growth and their

radial increment responds when the spruce budworm epidemic declines (Thomson and Van Sickle 1980).

The decline in volume increment due to defoliation by the spruce budworm has been calculated for balsam fir stands (Kleinschmidt et al. 1980b) and for individual trees and stands in the East (Solomon 1983). The decline in growth response of trees with a known defoliation history may not be applicable to trees with different defoliation histories. Also, the growth response over the bole when trees within stands are protected has not been determined. Therefore, to provide the forest manager with estimates of tree growth response, dominant and codominant balsam fir trees with different defoliation and protection histories were compared.

Methods

In 1978, sixteen even-aged 0.01 hectare plots were selected on well-drained sites in northwestern Maine (Kleinschmidt et al. 1980b). The plots, located in predominantly fir stands, had diverse defoliation histories between 1973 and 1978. In 1980 and again in 1982, additional plots were located in similar areas in order to extend the range of defoliation histories, species composition, and ages of the sample plots. Each plot was selected in a portion of the stand with minimal mortality and no other disturbances. Preliminary annual defoliation estimates were made, using reports from the Maine State Forest Service and visual examination of branch samples.

On each plot the species, diameter at breast height (dbh), and crown diameter were measured and recorded. Each tree was felled and cross-section discs taken above the butt swell, at breast height, at 1.5 m intervals along the bole to the base of the crown, and then at 1.0 m intervals. Disc height and total height were measured. Along an average radius on each disc the bark thickness and annual radial increment were measured or remeasured with a MEASU-CHRON Digital Micrometer to 0.01 mm.¹

An average branch was sampled from the third, sixth, seventh, and eighth or eleventh whorl from the top of each tree, depending upon the plot. The age at which the whorl formed was determined by sectioning and aging the bole on either side of the whorl. Foliage was removed by age class of needles for each branch; those older than 6 years were combined into one age class. The foliage was then oven dried (105°C) and weighed. The amount of defoliation was estimated

^{1/}The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable.

by comparing the actual weight of each age class of foliage remaining on the sampled branch to the predicted nondefoliated weight of comparable foliage (Kleinschmidt et al. 1980a). Kleinschmidt's equations were used to predict the foliage weight for age classes 1 through 5 on each sample branch in the top half of the crown of each tree. After each age class was weighed, the predicted and measured foliage weights were summed over the sample branches for each tree. The proportion of foliage remaining was estimated by dividing the actual weight by the predicted weight, and the percent defoliation for each tree was determined. The plot defoliation was estimated as the average defoliation of the trees on the plot used in the analysis.

The annual volume increment for the past 20 years and total volume inside bark were calculated for each tree. An algorithm was used to predict volume increment and the predicted was compared to the actual volume increment for each tree. The annual volume increment, both predicted and actual, was added to the total inside-bark volume. The individual tree's growth reduction was estimated from the difference between these volumes. An average was then determined for either dominant or codominant trees in each of the different defoliation and protection histories.

Results and Discussion

The bole volume growth of balsam fir declines as the severity of the defoliation history increases (Kleinschmidt et al. 1980b). Since balsam fir can retain its foliage for 8 to 10 years, different amounts of annual defoliation result in less current foliage being produced and eventually reduce the amount of foliage available

for tree growth. A model was developed to predict the amount of current foliage produced and the amount remaining in each age class (Hayslett and Solomon 1983). The reduction in the amount of foliage in the older age classes reduces bole volume growth (Solomon In Press). These results for balsam fir seem to relate different age classes of foliage to the growth of different sections of the tree.

Forest managers have sought to reduce the loss in volume growth caused by defoliation and to keep trees alive by protecting them. Protecting trees reduces budworm populations and provides for more current foliage to be passed on to successive age classes as the tree ages.

One-Time Protection

To show the growth response of trees to a single year of protection, four dominant fir trees were cut from one plot in 1978, after 5 years of defoliation with protection in 1976. The trees were 52 years old and had an average dbh of 19.4 cm. The average annual amount of foliage available for tree growth is predicted for each age class (Table 1). As the amount of defoliation caused by budworm continued to increase annually, the amount of current foliage retained each year decreased.

The reduction in foliage eventually causes a reduction in radial growth along the bole of the tree. (Figure 1). In 1974, 2 years after the start of defoliation, there is a slight decline in growth rate with a greater reduction in the upper boles. In 1976, 3 years after the start of defoliation, a more substantial reduction occurs in the lower bole near breast height. As can be seen in Table 1, 1976 is the year that the

Table 1. Predicted average annual total foliage weight in kg by classes for four dominant defoliated balsam fir trees protected one time.

Year	Average	Age Classes								Total ^a
	Defoliation (%)	Current	1	2	3	4	5	6+		
1972	--	4.65	4.02	3.45	2.78	2.20	1.55	0.78	14.78	
1973	57	2.10	4.50	3.85	3.12	2.30	1.60	0.92	16.30	
1974	59	1.75	2.02	4.30	3.50	2.60	1.68	0.98	15.08	
1975	97	0.10	1.70	1.95	3.92	2.90	1.88	1.00	13.35	
1976	25 ^b	3.45	0.10	1.62	1.78	3.25	2.10	1.12	9.97	
1977	40	3.02	3.32	0.10	1.48	1.48	2.35	1.25	9.98	
1978(Predicted)	--	----	2.91	3.20	0.10	1.22	1.06	1.40	9.89	
1978(Actual) ^c	--	----	3.82	2.94	0.06	0.45	0.66	0.96	8.89	

^a Total includes 1 to 6+ age-classes

^b Protected

^c Estimated actual foliage weight by age classes using branch samples

Figure 1--Annual radial increment in mm at standardized heights above ground for dominant defoliated and nondefoliated balsam fir trees protected one time.

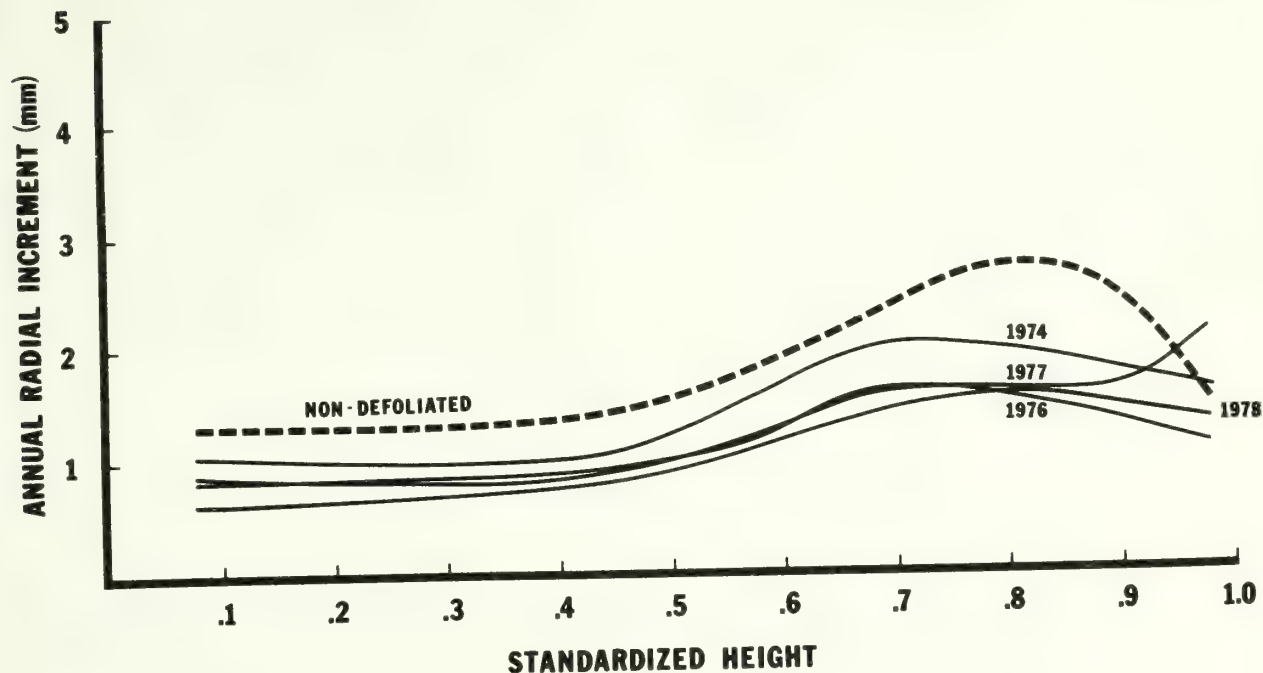


Table 2. Actual and predicted average annual volume increment and total volume for trees with different defoliation histories and protection intensities, in thousands of cubic centimeters.

	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
PROTECTED ONE TIME											
Defoliation (%) --		57	59	77	25 ^a	40	--				
Annual											
Actual	8483	8531	8400	8709	6762	7337	6344				
Predicted	12889	13382	13854	14291	14716	15126	15515				
Loss (%)	--	36.25	39.37	39.06	54.05	51.49	59.11				
Total											
Actual	205784	214315	222714	231423	238184	245522	251865				
Predicted	220326	233708	247562	261853	276569	291695	307210				
Loss (%)	--	8.30	10.04	11.62	13.88	15.83	18.02				
MODERATELY PROTECTED											
Defoliation (%) --		60	80	69	53 ^a	39 ^a	48	81 ^a	--		
Annual											
Actual	6179	6658	6680	6564	5289	4161	4474	4264	3447		
Predicted	5104	5258	5424	5599	5780	5968	6152	6347	6553		
Loss (%)	--	-26.62	-23.16	-17.24	8.49	30.27	27.28	32.83	47.39		
Total											
Actual	129968	136626	143306	149869	155158	159320	163793	168057	171504		
Predicted	123437	128695	134119	139718	145498	151466	157618	163965	170518		
Loss (%)	--	-6.16	-6.85	-7.27	-6.64	-5.19	-3.92	-2.50	-0.58		
INTENSIVELY PROTECTED											
Defoliation (%) --		15	70	90 ^a	70	86 ^a	71 ^a	77 ^a	45 ^a	27 ^a	--
Annual											
Actual	6826	7055	8038	7775	6467	4417	3592	6356	10246	9043	7346
Predicted	6963	8075	9266	10494	11676	12763	13664	14300	14608	14578	14245
Loss (%)	--	12.63	13.26	25.91	44.61	65.39	73.71	55.55	29.86	37.97	48.34
Total											
Actual	66404	73459	81496	89271	95738	100155	103747	110103	120349	129392	136750
Predicted	61124	69199	78465	88959	100635	113399	127063	141363	155971	170550	184795
Loss (%)	--	-6.16	-3.86	-0.35	4.87	11.68	18.35	22.11	22.84	24.13	26.00

^a Protected

reduced foliage from 1973 enters the 3-year-old age class. The trees were protected in 1976, but the volume increment over the whole bole continued to decline through 1976 to 54 percent (Table 2). The growth in the upper bole increased slightly in 1977 as the protected 1976 foliage entered the 1-year-old age class. The annual volume growth in 1978 declined below the 1976 level (Table 2).

The average cumulative total volume growth for the dominant trees declined 18 percent below that predicted from a continuous function based on an average of the 5 years before defoliation (Table 2). This method produced results similar to those published previously for the average of all trees on the plot (Kleinschmidt et al. 1980b).

Moderate Protection

A plot cut in 1980 was analyzed after 7 years of defoliation with protection in 1976, 1977, and 1979. The foliage on three codominant trees was modeled by age class from the beginning of defoliation in 1973 (Table 3). The trees were 52 years old and had an average dbh of 17.3 cm. The annual foliage production declined for the first 3 years and then increased in 1976 after protection. The radial growth in the lower bole for the same corresponding time was not different from the average annual radial growth during 5 nondefoliated years (Figure 2). The growth decline can be seen first in the upper bole in 1975, 2 years after the start of defoliation. In 1976, the fourth year of defoliation and the

first year of protection, the growth decline was substantial over the entire bole of the tree, causing a decline in the lower bole at breast height. The annual volume increment increased considerably in 1976 and 1977 (Table 2).

After 2 consecutive years of protection in 1976 and 1977, the current and 1-year-old foliage increased. However, there was less 3- and 4-year-old foliage because of the defoliation in 1973 and 1974. Thus, in 1977, the radial increment increased in the upper bole but continued to decline in the lower bole (Figure 2). The improvement in volume growth can be seen in the years of 1978 and 1979, when the annual growth loss is less (Table 2). Although the annual volume increment increased with protection, the negative percent growth loss for the total bole continued, because of the insensitivity of the model to codominant trees. Thus the total actual volume remained larger than that predicted, starting in 1976.

In the three years from 1978 to 1980, the stand was protected once. The current foliage did not increase in 1978, but a major foliage increase occurred in the 2-, 3-, and 4-year-age classes successively. These increases correspond to the radial increment (Figure 2) and volume increment (Table 2) remaining about the same for the same period of time. This seems to indicate that the 2 years of protection kept the volume growth from declining. And protecting the current foliage in 1976 reduced the growth loss as that increase in foliage reached each succeeding age-class of needles in 1978, 1979, and 1980.

Table 3. Predicted average annual total foliage weight in kg by age classes for three codominant defoliated balsam fir trees with moderate protection.

Year	Average Defoliation (%)	Age Classes							
		Current	1	2	3	4	5	6+	Total ^a
1972	--	3.04	2.63	2.24	1.82	1.42	1.01	0.50	9.62
1973	60	1.35	2.94	2.52	2.04	1.50	1.04	0.59	10.63
1974	80	0.63	1.30	2.82	2.92	1.68	1.09	0.63	9.81
1975	69	0.60	0.61	1.25	2.56	1.90	1.22	0.66	8.20
1976	53 ^b	1.01	0.58	0.59	1.14	2.12	1.37	0.73	6.53
1977	39 ^b	1.76	0.97	0.56	0.53	0.94	1.54	0.82	5.36
1978	48	1.50	1.70	0.93	0.51	0.44	0.68	0.92	5.18
1979	81 ^b	0.55	1.45	1.63	0.85	0.42	0.32	0.52	5.19
1980(Predicted)	--	----	0.53	1.39	1.48	0.70	0.31	0.52	4.67
1980(Actual) ^c	--	----	0.79	1.49	2.02	0.61	0.39	0.70	6.00

^a Total includes 1 to 6+ age-classes

^b Protected

^c Estimated actual foliage weight by age classes using branch samples

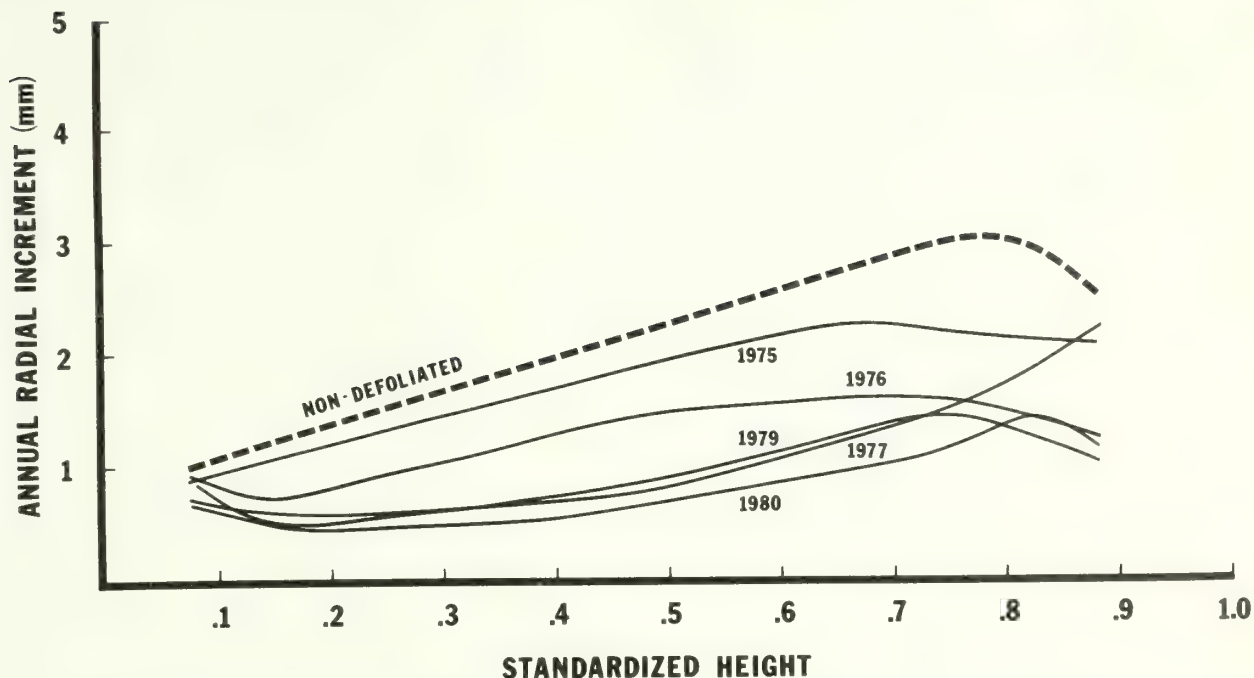


Figure 2--Annual radial increment in mm at standardized heights above ground for codominant defoliated and nondefoliated balsam fir trees moderately protected.

Intensive Protection

A plot cut in 1982 was protected for 6 years during 9 years of defoliation. The trees were 36 years old with an average dbh of 15.6 cm. The average foliage on two dominant trees is predicted by age classes starting in 1973 (Table 4). The defoliation of the current foliage in 1973 and 1974 caused a reduction in the amount of foliage that remained on the tree to become the foliage in the third- and fourth-year age class 4 years later.

The decline in current foliage 4 years after the start of defoliation is similar to that in the previous categories of protection. For these years the levels of defoliation are moderate, and as the defoliation continues the resulting growth response declines, first in the upper bole and then in the lower bole (Figure 3). In younger trees the crown covers most of the bole and a growth response over the whole bole would be noticed (Piene 1981). Similarly, in older trees the growth decline occurs in the crown but does not become distinguishable until several years later. The apparent relationship between percent defoliation and increment (Alfaro et al. 1982) may not be accurate, depending on how and where it is measured.

In 1976, the radial increment is almost constant along the entire bole. The radial growth at breast height is about the same for 4 years after the start of defoliation because defoliation is low in the first year and a

sizeable amount of foliage remains to become the third age class of foliage in 1976 (Table 4).

The decline in radial increment at breast height occurred in 1977, 4 years after the start of defoliation. The first protection in 1975 had minimal influence on tree growth (Severe defoliation can occur within a protection zone because of wind drift, timing, weather, etc.). The increased foliage in 1976, when defoliation was less, resulted in an increase in radial growth in the upper bole in 1977 and 1978. The average annual volume increment suffered considerable loss through 1978 because radial growth in the lower bole continued to decline (Table 2).

Continuous protection started in 1977, but the defoliation remained high (Table 4). The slight increase in foliage in the 1- and 2-year-old age classes produced an increase in radial increment (Figure 3). By 1978, after 2 years of continuous protection, the growth in the upper bole had increased and the radial increment in the lower bole continued to decline. In 1979, the lower bole growth increased after remaining current foliage increased in 1976, and survived to become the needles in the third age class. Protection during 1979-81 increased the amount of current foliage, which resulted in an increase in foliage remaining in the third and fourth age classes in 1980 and 1981 (Table 4). The corresponding annual increment continued to increase in the upper bole as well as the lower bole when more foliage remained to occupy older age classes.

Table 4. Predicted average annual total foliage weight in kg by age classes for two dominant defoliated balsam fir trees with intensive protection.

Year	Average Defoliation (%)	Age Classes							
		Current	1	2	3	4	5	6+	Total ^a
1972	--	1.12	0.95	0.79	0.63	0.46	0.33	0.32	3.48
1973	15	1.07	1.08	0.91	0.72	0.52	0.34	0.39	3.96
1974	70	0.41	1.03	1.03	0.82	0.60	0.38	0.41	4.27
1975	90 ^b	0.14	0.41	0.99	0.94	0.68	0.43	0.45	3.89
1976	70	0.37	0.13	0.38	0.90	0.78	0.50	0.51	3.20
1977	86 ^b	0.14	0.36	0.13	0.34	0.74	0.56	0.59	2.72
1978	71 ^b	0.32	0.14	0.35	0.12	0.28	0.54	0.67	2.10
1979	77 ^b	0.24	0.31	0.13	0.31	0.10	0.21	0.66	1.72
1980	45 ^b	0.60	0.23	0.30	0.12	0.26	0.07	0.34	1.32
1981	27 ^b	0.68	0.58	0.22	0.27	0.10	0.19	0.14	1.50
1982(Predicted)	--	----	0.66	0.56	0.20	0.22	0.07	0.07	1.78
1982(Actual) ^c	--	----	2.61	1.53	0.56	0.37	0.12	0.03	5.22

^a Total includes 1 to 6+ age-classes

^b Protected

^c Estimated actual foliage weight by age classes using branch samples

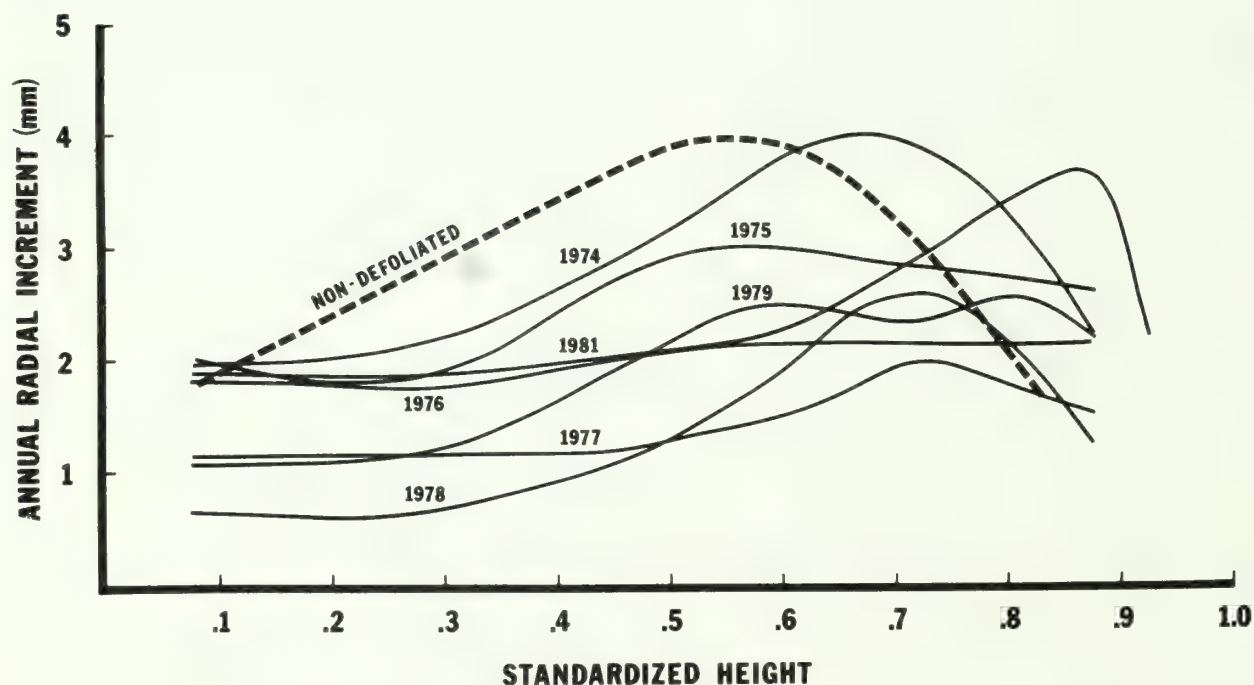


Figure 3--Annual radial increment in mm at standardized heights above ground for dominant defoliated and nondefoliated balsam fir trees intensively protected.

The annual volume increment continued to decline as the result of defoliation up to 1978; when the increase in foliage in the older age-classes caused an increase in growth (Table 1). The total volume increment remained about the same, reflecting the loss that had occurred previously. However, this increase in volume increment prevented a continued loss of total bole volume growth. Even after 4 more years of defoliation, the total bole volume loss reached 6 percent with protection.

Conclusion

The bole growth of balsam fir trees is related to the amount of foliage available. Since balsam fir can retain its foliage for 8 to 10 years, defoliation of the current foliage usually does not have a significant effect on tree growth that year or the next. In fact, reduced growth in the upper bole is only apparent 1 to 3 years after defoliation, when the reduced foliage has entered the 1- or 2-year-old age classes. Similarly, the radial increment in the lower bole is reduced when the reduced foliage reaches the third and fourth age classes.

One-time protection of full-grown, dominant balsam fir increases the radial increment in the upper bole, but has small effect on the growth decline at breast height. The use of moderate protection on full-grown codominant trees indicates that the decline in bole volume growth can be reduced and the level of growth maintained. Intensive protection of half-grown dominant balsam fir trees indicates that not only can the decline in bole volume growth be reduced, it can even be reversed and growth restored to previous levels. The growth response to continued protection happens first in the upper bole and then in the lower bole as the increased foliage survives enter the older age classes.

As the annual defoliation of balsam fir trees continues, the reduced amounts of current foliage become the foliage in each successive age class. When this reduction reaches the younger (1- and 2-year-old) age classes, the bole volume growth in the upper bole is reduced; when the same foliage enters the 3- and 4-year-old age classes, the volume growth in the lower bole is reduced. Maintaining a level growth rate or restoring a previous growth rate can be accomplished by planned regulation of protection. The protection of current foliage increases the amount of current foliage that is passed along to each succeeding age class.

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PREDICTING THE RISK OF SPRUCE BUDWORM DAMAGE USING HAZARD AND VULNERABILITY RATING SYSTEMS

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Seventeen hazard and vulnerability rating systems available for predicting the risk of spruce budworm damage in eastern Canada and the United States are reviewed and discussed. Hazard rating is short-term (often annual) mortality risk assessment that has been used extensively in planning annual spray operations. Vulnerability rating is a longer-term assessment of the risk of damage based on characteristics of stands, that is used primarily in prioritizing stands for harvesting. With the increasing usage of computer-based forest inventory mapping systems (often termed Geographic Information Systems), rating the vulnerability of individual stands as a function of stand characteristics becomes relatively easy for large forest areas.

Management of a forest during a spruce budworm (*Choristoneura fumiferana* Clem.) outbreak must involve judgements of the relative vulnerability (or risk of mortality) of different stands within the region. Stands vary with respect to species composition, age structure, site, etc., and all of these factors influence the degree of growth losses and tree mortality caused by budworm defoliation. Effective management should include directing harvesting operations to the most vulnerable stands to limit losses, concentrating protection (insecticide application) activities on the most vulnerable stands, and the use of silvicultural techniques to reduce damage. First, however, one must be able to determine the relative vulnerability of stands.

In general terms, there are some clear differences in vulnerability to budworm damage due to species and age-class of stands (MacLean 1980). Balsam fir (*Abies balsamea* (L.) Mill.) trees and stands are more vulnerable than spruce (*Picea* sp.) trees and stands. White spruce (*Picea glauca* (Moench) Voss) and red spruce (*P. rubens* Sarg.) are more vulnerable than black spruce (*P. mariana* (Mill.) B.S.P.). Mature and overmature stands are more vulnerable than immature stands. To give an idea of the damage to be expected in different types of stands, MacLean (1980) found average tree mortality levels of 85% in mature fir stands, 42% in immature fir stands, 36% in mature spruce stands, and 13% in immature spruce stands, based on plots from a number of studies. In essence, this information could be considered a very simple vulnerability rating

system, which could be used to select stands for treatment; more sophisticated, quantitative vulnerability rating systems are available, however.

In this paper, I will review the hazard and vulnerability rating systems that have been developed for use in eastern Canada and the United States.

Hazard Rating versus Vulnerability Rating - Is There a Difference?

Although the terms hazard rating and vulnerability rating have been used interchangeably and synonymously with "risk rating" in some studies, I am reserving a specific usage for each term in this paper, based on the commonly accepted usage in eastern Canada and Maine.

Hazard rating systems are used on an annual basis to predict severe budworm damage and probable tree mortality, primarily as a guide in formulating spray operations. These systems include estimates of budworm population level for specific areas, usually in terms of egg-mass density. Most hazard rating systems are based on methodology originated by Webb et al. (1956).

In contrast, vulnerability rating systems are used to rate the relative vulnerability to spruce budworm damage of different areas of forest, primarily for prioritizing stands for harvesting or management planning. In other words, vulnerability rating indicates the relative level of tree mortality which can be expected from a spruce budworm outbreak, as a function of stand characteristics. Vulnerability rating systems are based entirely on characteristics of the forest; they do not include an estimate of annual budworm population level, but implicitly assume a general outbreak scenario. Vulnerability rating systems date from those of Westveld (1945) and Balch (1946). In this paper, I have further divided vulnerability rating systems into two types: (1) empirical systems based on intuitive observations which produce relative ratings of stands, and (2) quantitative systems which predict the amount of mortality as a function of stand characteristics, through the use of regression or multiple regression equations.

Hazard Rating Systems

Hazard rating systems have been used extensively in Maine, the Maritime Provinces, Newfoundland, Quebec, and Ontario as an aid in planning spruce budworm spray operations. The various hazard ratings used in different jurisdictions have been described by Dorais and Kettela (1982). Most are based on the methodology of Webb et al. (1956), and differ only in detail. The one exception to this is the system used in Quebec, where hazard maps are constructed by overlapping a 4-yr sequence of defoliation maps and the current egg-mass infestation map (Hardy and Dorais 1976).

Calculation of hazard rating is shown in Table 1. Hazard values are based on data collected annually from aerial surveys and ground sampling points. Each value represents a composite estimate of current defoliation, previous defoliation, tree vigor, and budworm egg-mass density. The summed values of the various combinations of possible hazard conditions range from 0 to 20, and are rated as low (1-7), moderate (8-10), high (11-14), and extreme (>15) (Webb *et al.* 1956). Protection was originally applied in New Brunswick under conditions of high hazard (Webb 1955), but this has evolved into the current policy of protection under moderate or higher hazard (Dorais and Kettela 1982).

Table 1. Hazard rating systems are designed to predict severe budworm damage and probable tree mortality, as a guide in formulating spray operations (Webb *et al.* 1956, Dorais and Kettela 1982). Hazard is computed by summing values for estimates of current defoliation, previous defoliation, tree vigor, and number of budworm egg masses

Tally code	%	Hazard rating
(1) Current defoliation		
0	0	0
T-2	1-25	+1
3-6	26-65	+2
7-10a	66-100	+3
10b	100+	+4
(2) Previous damage or loss of old needles		
0	0	0
L (light)	1-25	+3
M (moderate)	26-65	+6
S (severe)	66-100	+9
(3) Tree vigor		
P (poor)		+2
F (fair)		0
G (good)		-2
(4) Egg masses per 10 m ² of foliage		
0		0
1-108		+1
109-260		+2
261-434		+3
435-1086		+4
1086+		+5
Sum of hazard rating values		Hazard
0-6		Low
7-10		Moderate
11-14		High
15+		Very high

Note: Hazard rating systems used in the Maritime Provinces, Newfoundland, Ontario, and Maine are all based on Webb *et al.* (1956), but vary in detail. The above system is that used in the Maritime Provinces (Dorais and Kettela 1982).

Empirical Vulnerability Rating Systems

Empirical vulnerability rating systems are summarized in Table 2. Eight systems have been developed for rating the vulnerability of stands or regional areas of forest, while two individual tree rating systems have been developed for classifying trees in selective cutting.

The 8 stand or regional vulnerability rating systems are generally quite similar, and provide an estimate of vulnerability in from three to five relative classes (Table 2). All systems are primarily based on the relative amount of balsam fir and (or) the maturity of fir, the most vulnerable species. Other factors, which have been included in specific rating systems, include the proportion of fir in the stand, the relative crown position of fir and hardwoods, the volume of spruce, tree vigor, stand density (or crown closure), stand size and isolation, topography, and climate. Calculation of vulnerability, generally involves using tables or formulae to assign numerical values to the various factors, summing the rating, and translating the numerical value into a specific vulnerability class. Although the rating systems are described in general terms in Table 2, it will be necessary in many cases for a user to refer to the original reference in applying a specific rating system to an actual area of forest.

To provide a better idea of the use of these systems, the most recently developed "vulnerability index" (Blais and Archambault 1982, MacLean 1982) is described in detail in Table 3. This rating scheme was developed by Canadian Forestry Service scientists from Ontario, Quebec, the Maritimes, and Newfoundland. It was designed to use presently available forest inventory data, and was meant to be used at a regional, or forest management unit, level. Calculation of the vulnerability index is based on the combined volume of fir and white spruce per unit area, the maturity of fir, the volume of black spruce and red spruce, and a climatic rating based on temperature and precipitation (Table 3). Four vulnerability classes (low, moderate, high, and very high) were defined following testing of the vulnerability index on forest units in several regions (Blais and Archambault 1982, MacLean 1982). Results of applying the vulnerability index to the province of New Brunswick, divided into a grid of 80 units, are shown in Figure 1. Testing of the index showed that the numerical ratings were in agreement with the actual fir mortality in over 90% of the management units in Quebec (Blais and Archambault 1982), and that the results in New Brunswick and Nova Scotia compared well with current knowledge of vulnerability in the region (MacLean 1982). The vulnerability index shows considerable potential as a management tool, although some forest managers have expressed the need for a comparable system for use at the level of individual forest stands. One recent attempt to design such a system is described in a later section of this paper.

Table 2. Summary of empirical vulnerability rating systems for predicting the risk of spruce budworm damage in eastern Canada and the United States. Vulnerability rating systems which predict the amount of mortality for different stands are presented in Table 4

Region	Reference	Description of vulnerability rating system
<u>Stand or regional rating systems - United States</u>		
Northeastern U.S.	Westveld (1945)	Vulnerability = volume bF (cords/ac) x BA average bF (in ²). Vulnerability was classed as low (20-99), medium (100-249), and high (>250).
Maine	McLintock (1949)	Vulnerability rated as low, medium, or high on the basis of fir volume per acre and maturity. High vulnerability was ≥ 4.0 cords/ac of mature fir.
Michigan, Minnesota	Graham (1956)	Vulnerability rated in 5 classes based on maturity of fir and relative crown position of fir and hardwoods.
Lake States	Bean and Batzer (1956)	Vulnerability rated in 5 classes based on age and volume of spruce-fir, proportion of fir, size of stand, and vigor.
<u>Stand or regional rating systems - Canada</u>		
New Brunswick	Balch (1946)	Vulnerability rated as low, moderate, or high, with highly vulnerable stands containing > 8 cords/ac, over half of which was fir.
New Brunswick	Morris and Bishop (1951)	Vulnerability rated in 4 classes as a function of stand density (crown closure), species composition (% fir), and maturity (height of softwood).
New Brunswick	van Raalte (1972)	Vulnerability rated on the basis of species composition, stand age - height, stand density, isolation, and topography.
Eastern Canada	Blais and Archambault (1982) MacLean (1982)	A numerical vulnerability index was calculated based on volume of fir and white spruce, maturity of fir, volume of red spruce and black spruce, and climate (see Table 3).
<u>Individual tree rating systems</u>		
Northeastern U.S.	McLintock (1948)	Rating of relative risk of damage for trees on a specific site, as expressed by growth rate. Individual trees are rated for crown class, crown ratio, and vigor.
Northeastern U.S.	Westveld (1954)	Individual tree "vigor-resistance" rating based on maturity, dominance, and crown class. Designed to be used in classifying trees for selective cutting.

The individual tree vulnerability rating systems of McIntock (1948) and Westveld (1954) originated in the northeastern United States, and were designed to rate the relative risk of damage for trees on a specific site. Both systems are based on factors associated with tree growth rate, including crown class (or dominance), crown ratio, vigor, and maturity (Table 2). This type

of system, which acts as a guide for selecting trees to cut or retain in individual stands, should be used in managing uneven-aged woodlots or stands. Westveld (1954) in particular advocated selective cutting techniques to make spruce-fir stands more resistant to spruce budworm outbreaks.

Table 3. Calculation of the vulnerability index (Blais and Archambault 1982, MacLean 1982) involves assigning numerical ratings to four components, and then determining a composite index, as shown below

(1) Combined volume of fir and white spruce (m ³ /ha)		Rating
1-6		1
7-13		2
14-20		3
21-27		4
28-34		5
35-41		6
42-48		7
49-55		8
56-62		9
63+		10

(2) Percentage of mature fir (>60 years old)		Rating
1-20		1
21-40		2
41+		3

(3) Combined volume of black spruce and red spruce, using the same numerical rating scale as for fir and white spruce (above). This factor is included only if the fir-white spruce volume is ≥ 27 m³/ha.

(4) Climate		Rating
warm-dry		8
warm-wet		4
cool-dry		4
cool-wet		0

where

warm = mean annual temperature of 2.5°C or more

cool = mean annual temperature below 2.5°C

dry = precipitation of 900 mm/yr or less

wet = more than 900 mm/yr

Vulnerability Index = (Volume rating bF-wS x Maturity rating bF) + Volume rating rS-bS + Climate rating

Vulnerability Index	Vulnerability Class
0-7	Low
8-15	Moderate
16-24	High
25+	Very high

Quantitative Vulnerability Rating Systems

Quantitative vulnerability rating systems, which relate the amount of mortality caused by spruce budworm damage in different types of stands to stand characteristics, are summarized in Table 4. Batzer (1969) developed the first system of this type, based on data from 23 stands in Minnesota, which predicted percent dead fir basal area as a function of percent spruce basal area, percent nonhost basal area, and fir basal

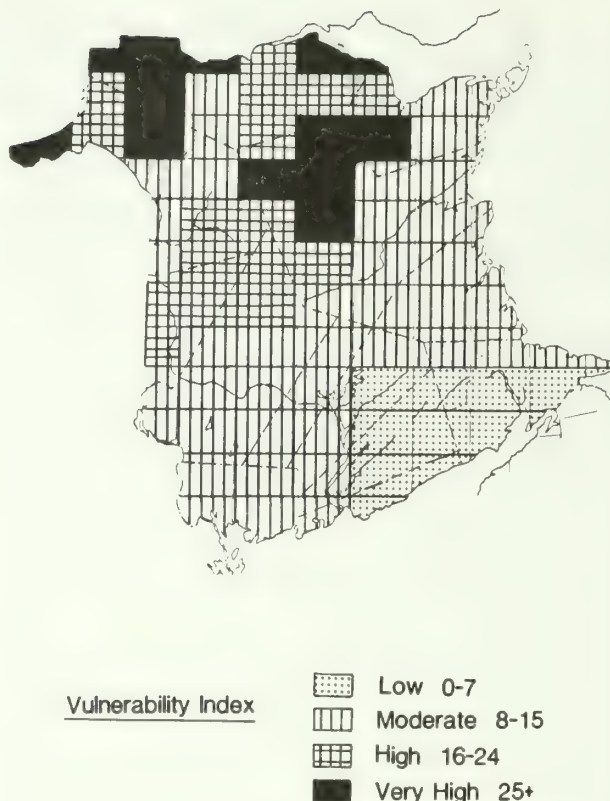


Figure 1. An example of application of the vulnerability index (described in Table 3) to 1:50,000 map sheet areas of New Brunswick (from MacLean 1982).

area (ft²/ac). This equation explained 56% of the variability in mortality among stands. Batzer and Hastings (1981) derived a similar equation based on an additional 35 stands in Minnesota, which predicted dead fir basal area from fir basal area and percent nonhost basal area, and explained 87% of the variability in mortality. Lynch *et al.* (1984) carried out analyses of mortality data from 24 and 41 stands in the eastern and western Upper Peninsula of Michigan. The equation for the eastern stands was similar to that of Batzer and Hastings (1981), except that "aspen" (*Populus* spp.) was substituted for "nonhost species", but the regression for the western Michigan stands predicted dead fir as a function of fir basal area, percent fir in stand (based on number of stems), and an index of the stand position on an east-west gradient (Lynch *et al.* 1984).

MacLean (1980) carried out a similar analysis, based on the combined data from a large number of previously published studies. Multiple regression analyses relating percent fir and spruce mortality to up to four independent variables failed to show strong relationships (R^2 or total explained variance < 50%), however, MacLean (1980) derived relationships between mortality in terms of basal area and the initial basal area of host species present. Four equations were

constructed, for mortality in mature fir stands with < 20% hardwoods, mature fir stands with > 20% hardwoods, immature fir stands, and mature spruce stands (Table 4). This analysis indicated that mature fir stands suffer consistently heavy mortality that often approaches 100%, a hardwood component in mature fir stands reduces the fir mortality slightly, and immature fir and mature spruce stands suffer lower, more variable mortality than mature fir stands (MacLean 1980). Data available from a recent study of spruce mortality in New Brunswick (MacLean *et al.* 1984) corroborate results of MacLean (1980), and indicate that typically one-quarter to one-half of the basal area or volume in spruce stands can be expected to die during an uncontrolled budworm outbreak. It would seem that our best model of tree mortality caused by spruce budworm, at least in a general forest management sense, is that of a constant proportion of the host basal area or volume (i.e., a linear relationship). This holds for both balsam fir and spruce, but the proportion of a stand that can be expected to die

during an outbreak varies considerably between these two species types.

In addition to the quantitative vulnerability rating systems in Table 4, a useful method for assessing current levels of spruce budworm damage from small-format aerial photographs (35-mm color positives) has been developed by McCarthy *et al.* (1983). A damage severity rating (four classes from low to severe) is obtained for individual stands based on photo-interpreted estimates of defoliation of living spruce and fir, and proportion of tree mortality in the stand. A test of the method showed that photo interpretation of forest damage condition matched ground inspection in seven out of eight stands surveyed (McCarthy *et al.* 1983). A self-instruction manual (Olson *et al.* 1982) is available as a training tool for those interested in spruce budworm damage assessment from small-format aerial photos.

Table 4. Summary of quantitative vulnerability rating systems that predict the amount of mortality caused by budworm damage in different types of stands

Region	Reference	Equation	R ²	n
Minnesota	Batzer (1969)	% Dead bF BA ^a = 70.144 + 0.529 (% spruce BA) - 0.636 (% nonhost BA) - 0.272 (bF BA in ft ² /ac)	0.56	23
Minnesota	Batzer and Hastings (1981)	Dead bF BA in ft ² /ac = 0.97 (bF BA in ft ² /ac) - 0.42 (% nonhost BA) - 4.1	0.87	35
Michigan ^b	Lynch <i>et al.</i> (1984)	(1) Dead bF BA in m ² /ha = 1.009 + 0.868 (bF BA in m ² /ha) - 0.081 (% aspen BA)	0.90	24
		(2) Dead bF BA in m ² /ha = 0.255 (bF BA in m ² /ha) - 0.154 (% bF in no. stems) + 0.270 (stand position on east-west gradient)	0.58	41
Eastern Canada ^c	MacLean (1980)	(1) Dead bF BA in m ² /ha = 1.00 (bF BA in m ² /ha) - 1.21	0.98	26
		(2) Dead bF BA in m ² /ha = 0.76 (bF BA in m ² /ha) + 0.47	0.93	11
		(3) Dead bF BA in m ² /ha = 0.59 (bF BA in m ² /ha) - 1.88	0.62	21
		(4) Dead spruce BA in m ² /ha = 0.31 (spruce BA in m ² /ha) + 0.89	0.54	13

^aPercent balsam fir (bF) basal area (BA) in dead trees (arc sine transformation).

^bEquations (1) and (2) from Lynch *et al.* (1984) are for stands on mineral soils in the eastern and western Upper Peninsula of Michigan, respectively.

^cEquations from MacLean (1980) are linear regression relationships of fir and spruce mortality (in terms of basal area) versus fir or spruce basal area, that were derived from a summary and reanalysis of data in the literature. Equations (1) to (4), respectively, represent mature fir stands with < 20% hardwoods, mature fir stands with > 20% hardwoods, immature fir stands, and mature spruce stands.

Vulnerability Rating and Harvest Scheduling Based on Stand Yield Projection

When the vulnerability index concept (MacLean 1982) was presented to forest managers in New Brunswick, it became apparent that while the index might have use as a general tool, there was a strong need for a system to rate the vulnerability of individual stands, and schedule the harvest progression of stands based on both vulnerability and their natural rate of decline due to overmaturity. A harvest scheduling/vulnerability rating system has subsequently been developed in New Brunswick (Erdle *et al.*, in preparation), which quantifies stand vulnerability in terms of expected volume losses during a spruce budworm outbreak. This system calculates two future yield projections for each stand in a management area, which represent protected (budworm spraying) and uncontrolled budworm outbreak (growth loss and mortality) situations. These two yield projections are then compared, and vulnerability is calculated as the difference in yield (cubic metres per hectare) between the protected and budworm-influenced stand projections at a given point in time. A harvest schedule for stands in the management area is determined as a function of both losses of yield due to stand overmaturity, and vulnerability. The method couples the New Brunswick Department of Natural Resources Geographic Information System, a wood supply model, and a simple stand development model to derive and produce a harvest schedule map that is compatible with a chosen harvest level (based on sustainable yield). The computing power of the Geographic Information System enables application of the technique to forest holdings of 100 000 ha or more (Erdle *et al.*, in preparation).

The procedure for establishing vulnerability to budworm is as follows. First, forest structure and stand yield data are compiled for the area of interest. This includes determining the spruce and fir proportions and age structure of each stand in the management area (e.g., proportions of immature, mature, and overmature spruce and fir). Secondly, the development of each stand is then projected for a 30-year period, assuming a continued protection program (control conditions), based on user-specified yield curves for different stand types and different spruce-fir components. Thirdly, the development of each stand is projected assuming a budworm outbreak and no protection, based on explicitly defined levels of growth loss and mortality for specified budworm outbreaks or defoliation conditions. These projections use the methodology outlined in MacLean and Erdle (1984); differing growth loss and mortality levels are applied to balsam fir and spruce in immature and mature stands. Fourth, the vulnerability to budworm is calculated for each stand as the difference between the yields of the control stand projection and the budworm yield projection. Note that in this system, vulnerability of a specific stand is not constant but varies with stand development and the level of budworm damage. Lastly, all stands in the management area are ranked with respect to (1)

the level of vulnerability, and (2) the rate of natural deterioration due to overmaturity, or 5-year volume losses (cubic metres per hectare) under control conditions. These rankings are then used to derive the harvest schedule for individual stands, i.e., which stands should be harvested in the 0-5 year period, 5-10 year period, etc.

The approach of using stand yield projections to rate vulnerability of individual stands appears to have considerable potential as a management tool. This method will allow managers to combine harvest scheduling, vulnerability rating, and protection (spray) planning into an integrated forest management system (Erdle *et al.*, in preparation). Protection can then be directed to where it is most needed and not wasted on stands scheduled for harvest in the near future. Similarly, stands that are most vulnerable or most severely damaged can be identified and harvested first to limit losses and to obviate protection measures. Perhaps most importantly, both vulnerability to budworm and results of protection activities can be evaluated in terms of expected stand yields and timber supply.

Summary and Conclusions

Seventeen hazard and vulnerability rating systems are available for estimating the risk of tree mortality and spruce budworm damage in areas ranging from Newfoundland to Minnesota and Michigan. In general, hazard rating may be thought of as a short-term, mortality risk assessment that is used primarily in planning annual spray operations, whereas vulnerability rating is a longer-term comparison of the risk of damage based on characteristics of stands. Hazard rating has been used extensively in eastern Canada and Maine. Vulnerability rating has been used to a certain extent in some areas, but appears to have much more potential use in forest management, particularly with the increased usage of computer-based forest inventory mapping systems. Calculation of the vulnerability of all individual stands in large management areas (100 000 ha or more) of forest can be accomplished easily using computer-based inventory systems.

Whereas hazard rating combines annual estimates of budworm population level, current and previous damage, and tree condition to forecast future damage, vulnerability rating is based solely on measureable characteristics of stands. Vulnerability rating therefore implicitly assumes that a general, "average" budworm outbreak occurs in all stands. It is important to realize that vulnerability rating can only produce a general, "average" estimate of tree mortality and budworm damage for stands. To the extent that budworm defoliation in an actual stand varies from that of the "average", assumed outbreak, mortality or vulnerability will also vary. That is, if the budworm outbreak is less severe in one of two otherwise identical stands, the level of tree mortality in that stand will also be less, but

vulnerability would be predicted to be similar. This caveat applies to both empirical and quantitative vulnerability rating systems; these systems should be used to provide a comparative rating of the risk of damage in different stands or management units of forest, rather than an absolute estimate of expected tree mortality for specific stands.

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Abstract

Spray deposit was measured on conifer foliage using Kromekote® card/glass plate units following aerial applications of nine pesticide formulations under different conditions. With the oil-based mixtures, the non-volatile medium had a higher viscosity and provided a greater deposit. Results with the water-based mixtures were variable because of the presence of different ingredients and application conditions.

Introduction

In aircraft application of pesticides for spruce budworm control, formulation properties and meteorological conditions influence the behaviour of the sprayed material from the point of emission to the target level and its deposition on the target surface (Smith and Burt 1970; Ware *et al.* 1970; Butler *et al.* 1969; Burt and Smith 1974; Perry *et al.* 1977).

Spray droplets of formulations containing volatile ingredients undergo in-flight evaporation resulting in decreased droplet sizes and deposit of the sprayed material (Seymour 1969; Joyce and Beaumont 1978). Viscosity and surface tension are known to affect the droplet size spectrum of a liquid during atomization (Yates and Akeson 1973). The efficiency of spray deposition in forest tree canopies would therefore depend indirectly on formulation properties, if the spray delivery conditions, crop canopy and meteorological factors were to remain the same in different applications. The influence of chemical structure has also been demonstrated on increased target deposition and decreased off-target deposit of sprays (Kaupke 1965; Limer *et al.* 1966). The present paper provides deposit data obtained from aerial spray trials of four aminocarb and two fenitrothion formulations, a blank formulation and two *Bacillus thuringiensis* (B.t.) formulations. The objective is to understand the role of formulation properties, application conditions and meteorological factors on spray droplet spectra, droplet density (droplets/m²) and spray volume deposits per unit area of crown foliage and ground sampling units.

Materials and Methods

Details on spray formulations, experimental blocks, sample trees, spray application conditions and meteorological factors are given in Tables 1, 2 and 3.

The ground sampling units used were the Kromekote® card/glass plate system developed by Randall (1980). These were placed in the clearing of about 5 to 6 m radius made around each sample tree. The trees were chosen to be of nearly uniform canopy size, height (~12 to 14 m) and DBH (~15 to 18 cm). For the June experiments, foliage of the previous year's growth was sampled randomly from the mid-crown at 1 h after spraying. For the August experiment however, mature foliage of the same year was sampled. The ground sampling units were also collected at 1 h after spraying. All samples were transported immediately to the mobile laboratory in the field where the foliage was frozen at -20°C. The glass plates were eluted with a suitable solvent and the eluates were stored in bottles away from heat and sunlight.

At the end of the field trials, the samples were transported to the FPPI laboratory, and the glass-plate extracts were analyzed by spectrofluorometry for obtaining the spray volume deposit per unit area (Tables 2 and 3). The Kromekote® cards were examined by microscopy to evaluate droplet stain sizes and droplet density. Spread factor was determined for the spray mixes to convert the stain sizes into the corresponding aerodynamic droplet sizes before evaluating the size spectrum, number and volume median diameters (NMD and VMD) and maximum diameter (D_{max}) (Tables 2 and 3). Foliage samples were homogenized with a suitable solvent, subjected to a column cleanup procedure and concentrated for the determination of the AI by GLC according to the procedures (Sundaram 1974; Szeto and Sundaram 1980). For SPA-3409, B.t.I and B.t.II, the GLC method could not be used since they contained no chemical insecticide, and therefore, spectrofluorometry was used to measure the fluorescent dye present in foliar deposits. Deposit concentrations were measured in ppb (ng AI per g foliage or ng dye per g foliage). (Tables 2 and 3.)

For determining the physical properties of formulations, viscosity, surface tension and droplet evaporation rates were measured at the temperatures encountered in the field (Tables 2 and 3). Viscosity was measured using Ostwald's viscometer. Surface tension was determined using the capillary rise method (Maron and Prutton 1965). To measure the rates of evaporation, droplets of defined sizes were produced in the laboratory using the rotary device designed by Rayner and Haliburton (1955), and were captured on glass fibre of known thickness and the droplet diameters were measured by microscopy at various time intervals at the temperatures encountered in the field, under almost still air conditions. The evaporation characteristics of formulations were expressed as the residual percentage of droplet volume remaining after the evaporation of the volatile components (Tables 2 and 3).

Table 1. Spray Formulations, Dosage and Application Rates

Formulation Abbreviation	Composition (v/v%)	Dosage (AI/ha)	Application Rate (L/ha)	Treatment Time and Location
AA-3409	Matacil® 180F 25.93; Atlox® 3409F 1.27 Water 72.27; Rhodamine B 0.53	70g ^a	1.5 ^a	June 1981; New Brunswick
AID-585	Matacil® 180F 25.93; ID585® 72.07 Automate B Red 2.00	70g ^a	1.5 ^a	June 1981; New Brunswick
AS-6N	Matacil® 180D 25.93; Sunspray® 6N 72.07 Automate B Red 2.00	70g ^a	1.5 ^a	June 1981; New Brunswick
SPA-3409	Sunflower oil 7.00; Atlox® 3409F 1.50 Water + 7g polymer 90.50; Rhodamine B 1.00	-	3.0 ^b	August 1981; Ontario
AT-100	Matacil® 180F 25.93; Triton® X-100 10.7 Water 70.07; Rhodamine dye 1.00	70g ^a	1.5 ^a	June 1982; New Brunswick
FCT-100	Fenitrothion tech. 10.90; Triton® X-100 10.7 Cyclosol® 63 24.00; Water 61.10 Rhodamine dye 1.00	210g ^c	1.5 ^c	June 1982; New Brunswick
FT-100	Fenitrothion tech. 10.9; Triton® X-100 10.7 Water 77.40; Rhodamine dye 1.00	210g ^c	1.5 ^c	June 1982; New Brunswick
<i>B.t.I</i>	Thuricide® 48B 25.00; Water 74.70 Chevron sticker 0.10; Erio Acid Red 0.20	30 BIU ^d	9.45 ^d	June 1982; Ontario
<i>B.t.II</i>	Thuricide® 48B 25.00; Water + 2.73g polymer 39.80 Water + 2.19g sticker 35.00; Erio Acid Red 0.20	30 BIU ^d	9.45 ^d	June 1982; Ontario

^a Formulation was applied twice at 5 day interval, each at 70g/1.5L/ha to provide a total of 140g/3.0L/ha.

^b Formulation was applied twice at the same time, each at 1.5L/ha to provide a total of 3.0 L/ha.

^c Formulation was applied twice at 5 day interval, each at 210/1.5L/ha to provide a total of 420g/3.0L/ha.

^d Formulation was applied twice at the same time, each at 15 BIU/4.725L/ha to provide a total of 30 BIU/9.45L/ha.

Results and Discussion

Droplet density values are presented in Tables 2 and 3 as the Mean \pm SD for each formulation. In the 1981 trials, the two oil-based mixes, AID-585 and AS-6N, provided higher droplet densities and larger droplet sizes than the Atlox®-based emulsion. This is probably due to the 80% relative humidity (RH) at which AA-3409 was sprayed. Water-based mixtures are known to undergo in-flight evaporation at RH values 80% and below (Matthews 1979), resulting in smaller droplet size spectrum. Since the two oil-based mixtures have evaporation characteristics independent of RH values of the ambient air, they produced droplet spectrum

dependent upon temperature only. Between the two oil-based mixes, the non-volatile Sunspray® oil-based AS-6N provided a higher value and this is attributable to the physical properties such as higher viscosity and lower evaporation characteristics. In the case of the blank formulation SPA-3409, the low RH of 80% is expected to cause lower droplet density and smaller droplet sizes, but the presence of a polymer (Table 1) had caused the largest droplet spectrum observed (Table 3), and because of this the droplet density was the lowest and so was the coverage. However deposits on foliage and glass plates was the highest. This is because of the large droplet sizes which contributed to a large droplet volume and mass deposit.

Table 2. Spray Application Details, Weather Factors, Formulation Properties and Spray Deposit Data for Aminocarb Formulations

Formulation	AA-3409 ^a	AID-585 ^a	AS-6N ^a	AT-100 ^b
Spray Block Size (ha)	50	50	50	50
Aircraft Type	Cessna 188	Cessna 188	Cessna 188	Cessna 188
Aircraft Speed (km/h)	160	160	160	160
Atomizer Units	4 x AU3000	4 x AU3000	4 x AU3000	4 x AU3000
Spray Height above Canopy (m)	30	30	30	30
Emission Rate (L/min)	24.5	24.5	24.5	23.7
Wind Speed (km/h) at 10m above ground)	0.25	0	0	5 ± 3
Temperature (°C) average of 10m and 1m values)	13.0	10.0	16.5	11.1
Relative Humidity (%)	80	96	73	81
Sample Trees (No.)	12 ^c	12 ^c	12 ^c	7 ^c
Ground Sampling Units (No.)	36	36	36	28
Droplet Density	6 ± 6	13 ± 6	15 ± 6	4.3 ± 4
D ₅₀ (μm)	28	35	45	20
D ₉₀ (μm)	36	39	68	32
Max (μm)	73	85	105	94
Leaf Deposit (ppb)	2300 ^d	2500 ^d	2800 ^d	700 ^d
Deposit on Glass Plate (ml/ha)	52.5 ^e	165 ^e	210 ^e	47.5 ^e
Viscosity (cp)	2.42	4.24	35.4	3.59
Surface Tension (dyne/cm)	31.0	29.2	31.3	31.5
Droplet Evaporation Characteristics (Limiting Residual Vol. %)	28.0	38.0	100.0	34.0

Data are from 1st application.

Data are from 2nd application.

Balsam fir [*Abies balsamea* (L.) Mill.].

ng/g of AI from GLC measurements.

Values are from spectrofluorometric measurements.

Table 3. Spray Application Details, Weather Factors, Formulation Properties and Spray Deposit Data for Fenitrothion, Blank and *B.t.* Formulations

Formulation	FCT-100 ^a	FT-100 ^a	SPA-3409 ^b	<i>B.t.I</i> ^b	<i>B.t.II</i>
Spray Block Size (ha)	50	50	3.0	50	50
Aircraft Type	Cessna 188	Cessna 188	Cessna 185	Cessna 185	Cessna 188
Aircraft Speed (km/h)	160	160	160	160	160
Atomizer Units	4 x AU3000	4 x AU3000	4 x AU3000	4 x AU3000	4 x AU3000
Spray Height Above Canopy (m)	30	30	6.0	30	30
Emission Rate (L/min)	23.7	23.7	12.0	38.0	38.0
Wind Speed (km/h) (at 10m above ground)	3 ± 1	3 ± 1	0 ± 0.5	9 ± 3	14 ± 3
Temperature (°C) (average of 10m and 1m values)	11.1	11.7	23.5	13 ± 1	17 ± 1
Relative Humidity (%)	75	87	80	75	75
Sample Trees (No.)	7 ^c	7 ^c	25 ^d	30 ^c	30 ^c
Ground Sampling Units (No.)	28	28	100	120	120
Droplet Density	5.3 ± 1.1	19.1 ± 7	3.3 ± 1.3	27 ± 9	21 ± 10
NMD (μm)	34	24	75	8	12
VMD (μm)	99	31	144	58	40
Dmax (μm)	138	130	380	143	155
Foliar Deposit (ppb)	800 ^e	1700 ^e	150 ^f	125 ^f	86 ^f
Deposit on Glass Plate (ml/ha)	55.08	74.08	4688	4568	3608
Viscosity (cp)	7.22	12.0	41.2	2.04	3.65
Surface Tension (dyne/cm)	33.3	32.1	38.0	25.5	38.9
Droplet Evaporation Characteristics (Limiting Residual Vol. %)	27.0	38.0	30.0	5.5	8.7

^a Data are from 2nd application.

^b Data are from both applications since the two applications were made at the same time.

^c Balsam fir [*Abies balsamea* (L.) Mill.].

^d White spruce [*Picea glauca* (Moench) Voss].

^e ng/g of AI from GLC measurements.

^f ng/g of dye from spectrofluorometric measurements.

^g Values are from spectrofluorometric measurements.

In the 1982 trials, the three emulsion formulations behaved somewhat similar to the AA-3409 emulsion in 1981, in producing a lower deposit on glass plates than those of the two oil-based formulations AID-585 and AS-6N. FCT-100 had significantly higher viscosity than AA-3409 and AT-100, but this did not seem to influence the deposit pattern to a great extent (Tables 2 and 3). However, FCT-100 had the highest viscosity among the four emulsions, AA-3409, AT-100, FCT-100 and FT-100, and it appears to cause the highest droplet density deposits on foliage and ground sampling units. However, this could also be due to the high RH of FCT-100 (Table 3). No direct inverse relationship is evident between viscosities and evaporation characteristics of these four emulsions. Between the *B.t.* formulations, *B.t.II* had a higher viscosity and lower evaporation, but it provided a lower droplet density and volume deposit, because of the wider droplet spectrum observed. Once again, the presence of polymeric components appears to cause larger droplet sizes.

It is worth noting that the two *B.t.* formulations, in spite of the favourable higher wind speed conditions (Table 3), failed to provide higher foliage deposits although they provided higher deposits on the ground sampling units (Table 3). This is probably because of the larger volume rates of application, which are known to provide a wider droplet spectrum (Joyce and Beaumont 1978). While evaporation of water from smaller droplets increased the proportion of fine droplets in the spray cloud which are too inefficient to impact on foliage, the presence of larger droplets, having a low sedimentation rate, resulted in greater ground deposits. This indicated the need to optimize the volume rates for every formulation and spray application systems.

In conclusion, the following are indicated in this paper:

An inverse relationship appears to exist between the viscosity and evaporation characteristics of oil-based spray mixes, i.e. the higher the viscosity, the lower the evaporation. Such a trend was not observed with water-based formulations.

With the oil-based spray mixes, the higher viscosity caused a larger droplet spectrum and higher deposits on foliage and on glass plates.

Surface tension values of all spray mixes did not vary to a great extent and consequently any influence on droplet size spectrum can be expected to be similar with all mixes.

The suitability of polymeric components should be judiciously evaluated for each formulation and spray application systems and for the target types. Otherwise polymers can only bring disadvantages, such as an undesirably large droplet spectrum.

It is essential to determine the optimum volume rates of emission for each formulation and spray delivery systems. Otherwise, volume

rates greater than the optimum level, would only increase ground deposition of sprays leading to ground contamination and wastage of pesticide materials.

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Introduction

One of the major objectives of the CANUSA
program has been to bring microbial control into
functional use in spruce budworm management and
control programs. *Bacillus thuringiensis* (Bt) is
the microbial agent with the greatest potential
to meet this objective, but until recently has
performed erratically in field operations. There
are many reasons for this erratic
performance--two reasons addressed in this paper
are: (1) The strain of Bt being used and (2), the
formulation-application-deposit of the material.

Bt Strain Research

Several years ago (1974), Dr. Howard Dulmage,
USFS, organized an international cooperative
research effort on the spectrum of activity of *Bt*
against major agricultural and forest pests,
including spruce budworms. The purpose of this
large interactive study was to calibrate known
genotypes and isolates of *Bt* to the standard *Bt*
HD-1S-1971 until 1980, HD-1S-1980 from 1980 on) and
compare activity of these isolates among the
major pest insects. Over 600 isolates, uniformly
prepared by Dr. Dulmage's laboratory, were
distributed to the major research groups
cooperating in this endeavor. Our laboratory was
involved in the screening of these preparations
against the gypsy moth and the eastern spruce
budworm. In the course of these screenings
against laboratory-produced spruce budworm (FPMI),
one of us (NRD) isolated several new *Bt*s that
exhibited greater activity against the budworm
than the commercially available strain (HD-1) and
most of the standardly produced HD isolates
examined in the screening. Morris and Moore
(1983) reported on the comparative potencies of
10 HD isolates against laboratory-produced
fifth-instar larvae. Data showed a 1200-fold
difference from the most active to the least
active strain. Similar data have been obtained
in our laboratory.

Table 1 illustrates the wide range of
activity of *Bt* isolates to spruce budworm
larvae--prior to formulation for field use.

TABLE 1
RANGE OF ACTIVITY OF *Bt* LABORATORY BIOASSAYED
AGAINST FOURTH INSTAR SPRUCE BUDWORMS.

<i>Bt</i> STRAIN	LC 50 (μ g)	LT 50 (days)
NRD-12	1.68	2.66
NRD-10	1.32	2.75
HD-1S-1980 (Standard)	3.62	5.08
HD-53	1.45	5.20
HD-278	12.92	5.10

All laboratory bioassays are conducted with
standard protocols using uniformly aged larvae
reared on artificial diet in a
temperature-controlled cabinet. Dose-response
data are obtained from more than one assay.
Coefficients of variation are about 40-45% with
the standard HD-1S-1980 reflecting the
variability of the response of spruce budworm
larvae.

The significance of the differences in
activity among all these *Bt* strains is that the
most effective strain, in terms of percent larval
kill or speed of larval kill, may not be in use
against the spruce budworm. This will certainly
have an impact on any suppression effort and will
have a major impact on any economics of *Bt* use.
Several isolates exhibit faster action, certainly
desired, but no greater larval mortality, thus
giving better foliage protection. Several strains
exhibit equal activity against the insect at
significantly lower dosages, certainly desired
from an economic point of view.

These large differences in activity of *Bt*
strains are further complicated by the
formulation-application aspects of the
problem--as discussed by Dr. Sundaram--which
involve the chemistry and physics of the total
formulation, its biological parameters, and the
physics, meteorology, and aerodynamics of
application.

Formulation Research

The formulation-application-deposit problem,
particularly with microbials, has been identified
by many researchers and in three major symposia
as the most critical area needing resolution for
regular utilization of these agents in pest
management systems, including the spruce budworm.

At the Center for Biological Control of Forest Insects and Diseases, we have begun to develop a formulation-application facility consisting of an aerial spray simulator, a sunlight simulator, an automatic drop counter, and a bioassay room. These facilities are in place at our Ansonia field site and are in the process of being calibrated and standardized. These facilities are designed to simulate aerial sprays and to evaluate, primarily, the biological effects of drop size, and density, stickers, deleterious sunlight wavelengths, adjuvants, volume, additives, carriers, and timing of Bt, NPV, and other microbial agents used against major eastern defoliating insects. The principal reason for developing the facility is to bridge the gap between laboratory analyses and actual field trials which as you all know involve large expenditures and have many uncontrollable factors.

Aerial Spray Simulator

The heated spray simulator is 16x12x12 feet with a base turntable with rotation adjustable from 0-3 r.p.m. Four smaller turntables, geared 3 times the rotational speed of the main turntable, are mounted above the main turntable. Experimental microbial sprays are delivered 12 feet above the turntables by a model 250 Beecomist¹ nozzle with a digitized rpm meter controlled by rheostat. The experimental formulations are delivered to the nozzle by slight airpressure to simulate 0.5-4.0 gallons per acre. A variable speed fan is mounted 3 feet above the nozzle to introduce down draft if desired.

Spray deposit is caught by plants, cards, petri dishes or other surfaces and then subject to simulated rain, sunlight, etc. for weathering testing, and the deposit is sized and counted in the droplet counter.

Droplet number and size is controlled by the formulation flow rate and amount, the nozzle speed, the turntable rotation, and the fan.

We are experiencing some difficulties with uniformity of deposit with low gallonages, and are presently modifying the flow system to the nozzle.

Figure 1, a, b, c, shows the spray simulator, and Figure 2 illustrates preliminary droplet distribution of 2 gallons per acre at different nozzle speeds.

¹The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable.



Figure 1.--a - external view of spray simulator

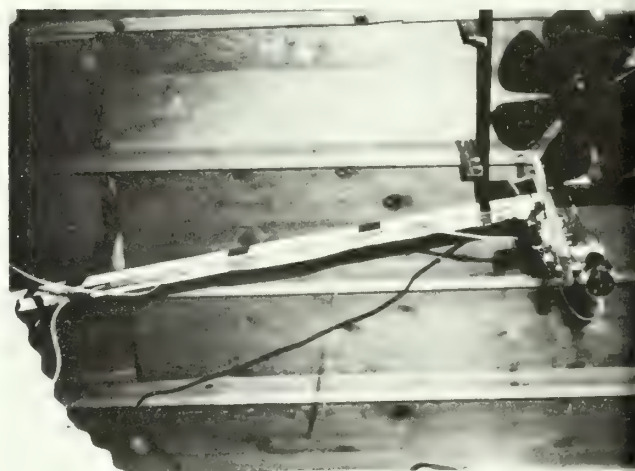


Figure 1.--b - nozzle and feed mechanism



Figure 1.--c - turntable

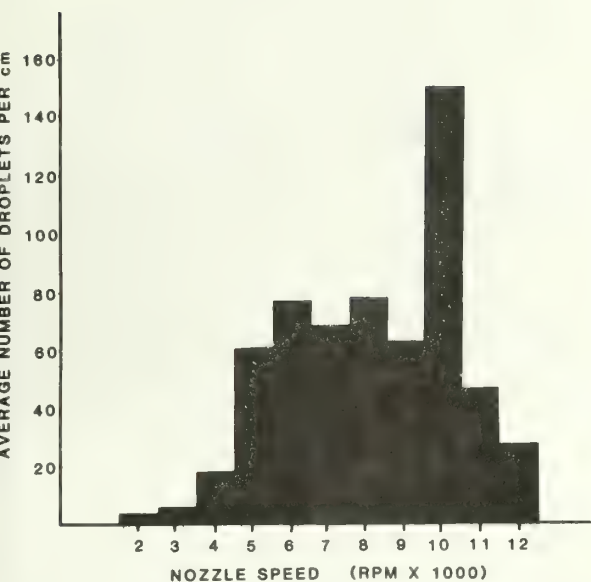


Figure 2.--Droplet spectrum at 2 gallons per acre
2 gallons per acre delivery volume.

Light Simulator

The sunlight simulator, designed by Dr. Conrad Mason, U.Mich., under a CANUSA grant, simulates the total flux of the sun at New Haven latitude in mid June (Figure 3). The simulator is 2x4 feet, has eight dual fluorescent fixtures each containing a sunlight and a black light of 40 watts each. The table and the fixtures are height-adjustable. The table was intended to give UV exposures approximating those outdoors, but recent calibrations have shown that more UV-B and UV-C are being generated than reaches the earth's surface at the New Haven latitude.

Preliminary results with tests indicate that the table will provide good information on U-V degradation of microbial formulations, but that modifications, by light filtration or rheostating will be required to simulate actual sunlight fluxes.



Figure 3.--Sunlight simulator with treated plants in position.

Droplet Counter

A Quantimet® Image Analyzer model 720 was acquired from the Pacific Northwest Forest and Range Experiment Station (Figure 4). This device automatically counts and sizes droplets in pre-determined bin-size ranges. A deposit surface can be sized, counted, and hard-copied in less than 30 seconds.

All experimental formulations tested in the spray tower can be sized and counted the same day as simulated application. Light-colored spray formulations do have to be dyed to provide contrast to the deposit surface.

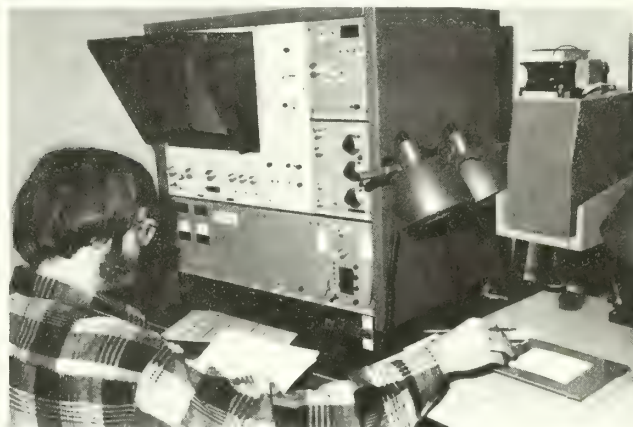


Figure 4.--Droplet counter with Kromecote card in position.

Future Direction of Formulation-Application Research

Optimal use of microbial agents in pest suppression or pest management systems, such as the spruce budworm Integrated Pest Management, will only come about by optimizing the formulation of the agent and delivering this formulation to the target pest most efficiently and effectively. Concurrently the most effective strain of the organism for the target pest must be properly selected.

Microbial insecticides are different from conventional insecticides. The active ingredient is a living entity, subject to biological enhancement or degradation. They are easily inactivated by physical phenomena. They are particulate, presenting quite different problems from soluble materials, and they are usually applied in a water-based formulation, thus increasing the evaporation-deposition problem.

Our plans revolve around the biological problems of droplet content, distribution of the active ingredient in the drop, the effect of drop size on biological content, the synergistic or antagonistic biological effects of U-V screens, stickers, stains and dyes, and anti-evaporation agents. The physical attributes of different delivery systems have biological effects on these agents. We hope to concentrate in these areas from the biological point of view rather than the conventional physical formulation-application research.

We hope to incorporate new developments in laser technology for droplet analysis, new information on sunlight wavelength effects on microbials, other than U-V, and new designs and improvements in application hardware and technology.

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The use of chemical insecticides for spruce budworm control from 1945 to the present will be reviewed. In the past 4 years, over 12 million hectares have been sprayed in eastern Canada and treated with 4 insecticides primarily, MATAcil, fenitrothion, Sevin and Orthene. Application rates, formulations and other characteristics of these insecticides will be presented. Recent research and development at the Forest Pest Management Institute with new formulations of MATAcil, fenitrothion and Sevin will be discussed as well as some new or recently resurrected insecticides such as Zectran, Sevin and permethrin.

Introduction

Chemical insecticides have been the most commonly used tools for spruce budworm control in Eastern Canada and North-eastern United States. There are a number of reasons for this. They are effective, easy to apply quickly to large areas at low volumes, and economical. Besides Bt, there are at present no other non-chemical options available which approach these attributes. Furthermore, extensive environmental impact studies have demonstrated that currently-used insecticides at registered rates and use patterns are relatively safe and do not result in unacceptable disturbances to environmental quality. Chemical insecticides have proven invaluable in protecting the forest resource from spruce budworm and we must ensure that they remain a viable control method so that forest managers will have a choice of options available to use in the future.

History of Insecticide Use

In Canada, 7 insecticides have been used over the past 40 years for the control of spruce budworm by aerial application to large areas (Nigam 1980). DDT was used extensively in operational control programs in several provinces at various times from 1945 to 1968. Aerial application of phosphamidon began in 1963 and this insecticide was used quite extensively until 1978. Zectran was

used on a small scale between 1969 and 1974 while operations with trichlorfon started in 1970 but it has not been used extensively since 1977. Of the insecticides in current use, control operations started with fenitrothion in 1967, with MATAcil in 1970 and Orthene in 1974 on a very small scale. Unlike the US, Sevin has only been used occasionally and on a very small scale for spruce budworm control in Canada. During the period from 1965 to 1980, approximately 12.5 million kg or 27.5 million lb. of these insecticides have been used on about 50 million hectares or 125 million acres to control spruce budworm.

Over the past 4 years, the major users of chemical insecticides for spruce budworm control have been the state of Maine, and the provinces of New Brunswick, Quebec and Newfoundland. In Maine, Sevin has been the major insecticide used during this period except in 1983 when MATAcil was the primary insecticide. Orthene has also been regularly used to a lesser extent and some Zectran was applied in 1983. The redevelopment and use of Zectran for spruce budworm control will be discussed later in this paper. Approximately 1.5 million hectares have been sprayed in Maine over the past 4 years. In eastern Canada fenitrothion and MATAcil have been the insecticides used almost exclusively for spruce budworm control during the past 4 years. In New Brunswick, approximately 7 million hectares have been sprayed, primarily with fenitrothion. In Quebec, approximately 3.3 million hectares have been treated primarily with MATAcil and some fenitrothion while during the past 3 years about 354 thousand hectares have been treated in Newfoundland. In total, approximately 12 million hectares or 30 million acres have been sprayed with Sevin, fenitrothion, MATAcil or Orthene between 1980 and 1983^{1/}.

Characteristics of Currently Used Insecticides

All of these insecticides are carbamate or organophosphorous chemicals which inhibit acetylcholinesterase, the enzyme which breaks down acetylcholine. Acetylcholine is a chemical which regulates the transfer of nerve impulses across nerve junctions. If it is not broken down, the acetylcholine accumulates and nerve impulses continue to be transmitted.

^{1/} Above statistics compiled with permission from Forest Pest Control Forum Reports, Unpublished Reports or Personal Communications.

Under such continuous stimulation, the nervous system cannot function properly and the insect eventually dies.

Aminocarb

MATACIL or aminocarb is a carbamate insecticide formulated and marketed by Chemagro Ltd. in Canada and Mobay Chemical Corp. in the US. Its acute oral toxicity and dermal toxicity to rats are 30 and 275 mg/kg (LD50) respectively. It is the most toxic of the 4 insecticides to spruce budworm larvae and is used at the lowest dosages. It is registered for aerial application in Canada at 52-90 g AI/ha with 1 or 2 applications a season. In the US, it is registered at 2.4 oz AI/acre in one application or 1 oz AI/acre in each of 2 applications 5 to 6 days apart. Typically, this insecticide has been applied in 2 applications at either 52 or 70 g AI/ha for each application. MATACIL 180-D or 1.8D Oil Soluble Concentrate containing 180 g aminocarb/l has been the formulation used previously. More recently, a new flowable formulation, MATACIL 180F or 1.8F containing the same concentration of aminocarb has been used operationally in some spray programs. It can be mixed straight with an oil carrier such as fuel oil or ID585, or with water with the addition of an emulsifier. This flowable formulation was developed to replace the previous formulation, MATACIL 1.8D which contained nonylphenol as the primary solvent. Concern had been expressed about the toxicity of nonylphenol to certain aquatic organisms which were more sensitive to this solvent than to aminocarb itself. The new formulation is much less toxic to fish than the previous formulation (Szeto and Holmes 1982).

This MATACIL 180F formulation was extensively tested at the Forest Pest Management Institute to determine its relative toxicity to spruce budworm in the laboratory, its spray characteristics, its efficacy in the field, as well as its environmental impact and fate in the forest ecosystem. The contact and residual toxicities of this flowable formulation were comparable to existing MATACIL formulations. In a double application at 70 g AI/ha in either ID585 or Atlox + H₂O it was as effective in controlling spruce budworm larvae and protecting balsam fir and spruce foliage as MATACIL 1.8D (Cadogan et al. 1984). Both MATACIL 180F mixes had very little observable impact on the forest songbird, benthic invertebrate, Atlantic salmon and brook trout populations monitored (Millikin 1982, Kreutzweiser 1982). Apart from relatively high concentrations in balsam fir needles, residues in air, stream water, stream sediment, aquatic

moss, fish, soil and litter generally disappeared quite rapidly indicating that this formulation has low persistence at this application rate (Sundaram et al. 1983).

Fenitrothion

Fenitrothion is an organophosphorous insecticide with an acute oral and dermal toxicity to rats of 330-800 mg/kg and 890-1200 mg/kg respectively. It is marketed by several companies under different trade names including Sumithion by Sumitomo Chemical Co., Folithion by Chemagro Ltd., Novathion by Cheminova and Accothion by American Cyanamid. It is about 3 times less toxic than aminocarb to spruce budworm larvae and is typically used at a dosage of 210 g AI/ha in each of 2 applications. It is registered in Canada for either a single application at 280 g AI/ha or 2 applications 4-6 days apart at 140-210 g AI/ha for each. New Brunswick is the major user of fenitrothion. They obtain ca 95% technical material and formulate it with the emulsifier, Atlox 3409F and Dowanol TPM for application as a water based mix, or to a lesser extent with Cyclosol 63 and ID585 as an oil based mix.

A new formulation of fenitrothion, Sumithion 20% Flowable has recently been developed by Sumitomo Chemical Co. which can be mixed directly with water without the addition of an emulsifier. This formulation is presently being evaluated at FPMI. Its mixing, spraying and storage characteristics are good. This flowable formulation is as toxic to spruce budworm larvae as other aqueous based fenitrothion formulations, both when larvae are exposed directly to it or when untreated larvae are exposed to treated foliage. Its residual toxicity is also comparable to other fenitrothion formulations. The efficacy of this product in controlling spruce budworm and providing foliage protection will be field tested this spring in New Brunswick.

Carbaryl

Sevin or carbaryl is a carbamate insecticide with low mammalian toxicity. The acute oral LD50 to rats is 560 mg/kg while the dermal LD50 to rabbits is greater than 2000 mg/kg. It is produced and marketed by Union Carbide Corp. Its toxicity to spruce budworm larvae is lower than the other insecticides and correspondingly, it is sprayed at the highest rates of application. It has been used extensively by Maine for spruce budworm control, most recently at a dosage of 6 oz AI/acre in each of 2 applications. It is registered for this purpose at 1 lb AI/acre. Sevin-4-Oil,

the formulation used, is a dispersion of finely ground carbaryl in oil designed to be mixed only with an oil such as kerosene or fuel oil as a carrier. It contains 4 lb carbaryl/US gallon. Union Carbide recently introduced a new formulation of carbaryl, Sevin FR, a suspension of microfine carbaryl in a water medium which can be mixed with water as a carrier. This formulation has been field tested extensively in Maine. It was also tested in the initial stages of our insecticide evaluation program at the Forest Pest Management Institute. Its direct contact toxicity to spruce budworm larvae was similar to Sevin-4-Oil and another formulation, Sevin XLR. The toxicity of Sevin FR to untreated larvae on treated foliage appeared to be about 4 times better than its contact toxicity. The residual toxicity of the 3 Sevin formulations was also similar except that Sevin FR in Dowanol TPM was more persistent than the same formulation in PA-3, an additive supplied by Union Carbide. This product was ready for field efficacy trials but its development has not continued further.

Acephate

Finally, Orthene or acephate is an organophosphorous insecticide which has been used on a small scale for spruce budworm control, particularly in Maine. It has a low mammalian toxicity with oral LD50 values of 866-945 mg/kg to rats and a dermal LD50 of more than 2000 mg/kg to rabbits. It is marketed by Chevron Chemical Co. It is slightly more toxic than Sevin to spruce budworm larvae and is currently being used in Maine at the registered dosage of 8 oz AI/acre in a single application. The formulation used is a Forest Spray Concentrate containing 85% acephate as a powder which is soluble in water.

Recent Developments with Chemical Insecticides

As indicated above, new formulations of current insecticides have been or are being actively developed for spruce budworm control. There are various reasons for this but a common feature of these formulations is that they can be sprayed with water which reduces the cost of application by eliminating the need for an oil carrier.

There are few new insecticides on the horizon with potential for spruce budworm control. In the future forestry will be almost entirely dependent upon insecticides developed for use in agriculture. Only a small portion of those developed for agricultural uses will be

suitable for forestry use. Furthermore, relatively few new insecticides are being introduced for any purpose because of the very high cost of development and because it is becoming increasingly more difficult to discover new compounds.

Having said this, there are some new or recently resurrected insecticides currently under development with potential for spruce budworm control. Zectran or mexacarbate is not a new insecticide but it has been recently reintroduced by Union Carbide Corp. who have purchased its rights from Dow Chemical. This insecticide had been tested and registered for spruce budworm control both in Canada and the US but it was not being marketed by Dow. It still has a registration for this use in the US but the registration has lapsed in Canada. Union Carbide is actively developing this insecticide again for forestry and other uses in the US and Canada. It was field tested for spruce budworm control in Maine last year.

Zectran is a carbamate insecticide which is structurally very similar to aminocarb. Its acute oral toxicity to various mammals ranges from an LD50 of 22 to 63 mg/kg while its dermal toxicity to rabbits is 500 mg/kg. New formulations are presently under development including a liquid formulation which is soluble in oil or which can be mixed with water to form an emulsion with the addition of a suitable emulsifier, and a water-based flowable formulation which can be mixed directly with water. These formulations are being extensively evaluated at FPMI. The contact toxicity of these new formulations to spruce budworm larvae is similar to the previous Dow formulation of Zectran and also to comparable formulations of aminocarb. Their toxicity to untreated larvae on treated foliage and Zectran's residual toxicity under natural weathering or greenhouse conditions are also comparable to aminocarb. Zectran will be field tested by FPMI this season for its efficacy against spruce budworm at 70 g AI/ha or 1 oz AI/acre in a double application.

Another carbamate insecticide, Larvin or thiodicarb from Union Carbide is in the initial stages of evaluation at FPMI. Its contact toxicity to spruce budworm larvae is intermediate to aminocarb and fenitrothion while its toxicity to untreated larvae on treated foliage is as good as aminocarb. Its residual toxicity in one test was excellent with no apparent decline in mortality over a 10-day period at a deposited dosage of 224 g AI/ha. This insecticide has also been tested extensively by the USDA Forest Service against western spruce budworm. Using an aerial spray simulator, Richmond

(1983) found that thiodicarb reduced larval populations by at least 90% at 105 and 160 g AI/ha and suggested that this insecticide should be tested in the range of 140-327 g AI/ha by aerial application.

Finally, I would like to discuss a relatively new group of insecticides, the pyrethroids and particularly one of them, permethrin. These pyrethroids are the most toxic insecticides to spruce budworm larvae ever tested at FPMI. Permethrin is about 3 times more toxic than aminocarb while deltamethrin is about 25 times more toxic than permethrin. Their residual toxicity against spruce budworm is also very good. Relative to their insect toxicity, the toxicity of these pyrethroids to mammals and birds is quite low. The acute oral toxicity of permethrin for example to various mammals is greater than 4000 mg/kg while the acute oral LD50 to several bird species ranges from 9900-38,000 mg/kg. However, these pyrethroids are highly toxic to fish and perhaps more importantly to aquatic invertebrates. The toxicity (48 hr TLM) of permethrin to several species of fish ranges from 1.8 to 38.5 micrograms per litre of water. At FPMI, permethrin was selected as a representative pyrethroid and intensively investigated to determine its effectiveness against spruce budworm by aerial application and its environmental impact, particularly in aquatic ecosystems. These studies have demonstrated that 2 aerial applications of permethrin at 17-18 g AI/ha can provide large scale spruce budworm control (DeBoo 1980, Zylstra and Obarymskyj 1981). No direct fish mortality in forest streams has been observed at this dosage or in fact at dosages of 70 g AI/ha or less suggesting that a safety factor to fish does exist with this insecticide (Kingsbury 1983). However, at 17.5 g AI/ha, permethrin causes severe disturbances to aquatic invertebrate communities in streams with likely secondary effects on fish populations including temporary growth rate reductions and movement of fish out of treated areas (Kingsbury 1983). For these reasons, Kingsbury (1983) has concluded that permethrin at 17.5 g AI/ha should only be considered appropriate for aerial use in situations where no such aquatic systems are present or where it can be demonstrated that they can be effectively buffered from the effects of treatment. Several scientists at FPMI are presently heavily involved in a research program designed to identify the size of buffer zones necessary to protect sensitive aquatic habitats from ground and aerial applications of permethrin for forestry use. Permethrin has recently received a commercial

registration in Canada for the control of spruce budworm and other forest insect pests in woodlands by ground application only at 17.5-35 g AI/ha in one application per season.

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Timing of spray applications for spruce budworm control requires consideration of an array of factors. The major ones are the stages of spring development of the insect and of its host trees. However, one should also consider densities of the insects and vigor of host trees, forest management and pest management goals, weather effects on insect activity, and associated insect pests.

Introduction

Effective control of spruce budworm with sprays depends on many factors, including choices of insecticides, dosages, spray volumes, swath widths, droplet size, etc., but proper timing of applications can be as important as any of the above. Sometimes, in large spray programs, decisions on when to spray are influenced by human pressures to get the work started, or finished, for financial reasons or to reduce morale problems due to prolonged inactivity of personnel. The sprays are not always applied at the best time with respect to larval vulnerability, host tree foliage development, and weather. In large spray projects, one cannot expect that ideal conditions will prevail at all times, but one should hope to exploit the good conditions often with the poorer ones avoided. As in statistics, we might consider two types of errors, Type I and Type II. In the Type I case, an over-cautious spray manager continually rejects spraying under conditions that are marginal on one basis or another; this may result in failure to complete the spray project by the time the insects have pupated or have already caused unacceptable damage. In the Type II case, an anxious spray manager may use all of the marginal spray time, finishing the spray project in a timely fashion, but a substantial proportion of the spray blocks may show poor protection. I suggest that, in practice, Type II errors are much more common than Type I errors.

Aerial sprays have been tried against spruce budworm moths in New Brunswick (Thomas et al. 1977) with little success. Greatest knockdown of female moths occurred among those which had already deposited their eggs (Thomas 1978).

All present spraying is directed against the larval or caterpillar stages while they are active and feeding, causing damage to the trees.

The timing of spray applications for reduction of insect numbers and their damage is determined by: (1) spring development of the

insect and (2) bud and shoot development of the host tree species concerned. But, decisions based on these major factors may also be modified by consideration of insect densities and target tree vigor, forest management and pest management goals, weather, and the presence of associated insects.

Insect Development

First instar larvae hatch from eggs in mid summer, enter diapause without feeding, and overwinter as second instars in silken hibernacula on the host tree branches. There have been no serious attempts to control those early, inactive stages. Upon resuming activity in May of the following year, the second instars mine within old needles of the host trees (Atwood 1944, McGugan 1954), there being no new foliage flushed as yet. On balsam fir and white spruce, third instar larvae have access to swelling buds which are mined. Instars IV - VI feed and develop within expanding current shoots until pupation. Needle-mining and bud-mining stages of the insect are generally considered as being poor targets for spray, since the larvae are enclosed within plant tissues. The normal timing of a single spray application, therefore, would be once buds have flared and the insects are actively feeding on the expanding shoots. While this period involves larval instars IV - VI, treatment is generally applied during peak instar IV to avoid the heavy damage caused by the later stages. In a given location, there is a period of two weeks before late instars cause serious damage.

When *Bacillus thuringiensis* is used, it is often recommended to apply treatment at peak instar III or between instars III and IV. The rationale for this early timing is that B.t. works more slowly than most chemical insecticides, and therefore, insects must be exposed to the bacterial insecticide earlier to avoid unacceptable damage to the trees. The validity of this argument is questionable, but it certainly does not apply now with the improved efficacy of B.t. formulations and dosages. Fast and Dimond (1984) suggest that a later timing of B.t. is more effective. This protects foliage as well as a single application of chemical insecticide; B.t. is rarely used in double (split) applications.

Chemical insecticides are frequently used as two (occasionally three) successive applications of a reduced dosage. This is done either to deal with the special timing problems involved with treating spruce (see Host Species and Their Development), or when spruce budworm numbers are very high in relation to the foliage resource available (see Insect Densities).

Adequate timing for spraying must take into account two trends. As larvae grow in the spring, they become more exposed and active, and make contact more readily with insecticides (Miller and Kettela 1975, Miller and Fisher 1978). While more insecticide is required to kill larger larvae (Nigam 1975), the larger forms contact and ingest

more spray deposit. However, the longer one waits to spray, the more defoliation one must accept (Webb 1955). Miller (1977) showed that 87 percent of total food consumption by budworm caterpillars occurred during the VI (last) larval instar. Treatments should be completed by early in this instar. Damage caused by the earlier stages is usually acceptable unless populations are unusually abundant, as at the peak years of an outbreak.

These comments on timing apply to balsam fir for the most part, and the special problems in dealing with spruce are discussed later.

Spruce budworm development is determined by code among budworm workers. L3 signifies larval instar III. L6 and P signify larval instar VI and pupae, respectively. Hereafter, this code will be used. Similarly, a distribution of several instars is quantified into a single larval index (L.I.) (Hardy et al. 1977). In a budworm population containing 20 percent L2, 45 percent L3, and 35 percent L4, L.I. would be calculated as:

$$\begin{aligned} (2 \times 20) + (3 \times 45) + (4 \times 35) / 100 = \\ (40 + 135 + 140) / 100 = \\ 315 / 100 = 3.15 \end{aligned}$$

L.I. of 3.15 is somewhat beyond peak L3; a value of 3.5 is mid-way between peak L3 and peak L4, etc.

Host Species and Their Development

The host species that are frequently damaged by the budworm are balsam fir, white spruce, and red spruce. Hemlock can also be severely damaged when mixed with fir or spruce. Black spruce is more resistant, but nevertheless, suffers severe damage and death in certain circumstances. Larch and pines are fed upon, but severe damage is not a problem.

Development of the spruce budworm in the spring seems best adapted to fir and white spruce. Swelling buds are normally available to the bud-mining third instars when they first need them. And, upon molting to L4, flushed buds and expanding shoots are available. Thus, at peak L4, budworms feeding on fir are feeding on expanding shoots, which also provide a target for the deposition of spray droplets. A single application of spray at this time is usually quite successful on fir.

White spruce presents a special problem because a cap of bud scales persists on the tip of the expanding shoot, providing protection from spray for small larvae. Delaying spray until the bud caps are shed, or larvae become large enough that bud caps provide little protection, is recommended. In mixed fir and white spruce, a split application is called for, the early one aimed at L4 on fir and the second against L5 on spruce.

Hemlock appears to be well protected by a single application of spray timed at the fourth instar on fir. Even though hemlock buds break about a week later than those on fir and white spruce, the budworm is not well protected as a bud miner on this species. Buds are so small on hemlock that complete concealment of the larvae is impossible (Hansen and Dimond 1982). Delay beyond this point can be costly on hemlock, however, since developing shoots are small compared to those of fir and spruce, and are destroyed with little feeding. Common spray timings for either fir or spruce generally work well on hemlock.

Bud break on red spruce, black spruce, and their hybrids is latest of the budworm hosts, about two weeks later than fir and white spruce (Greenbank 1963, Hansen and Dimond 1982, Varty and Godin 1983). This presents problems in control of budworm damage that are still not resolved. Treatment timed for fir is likely to find the larvae still mining buds on black or red spruce, and well protected from spray. Furthermore, the prolonged period of bud mining on the spruces results in a substantially greater level of destruction of shoots in the bud stage than on fir or white spruce (Hansen and Dimond 1982, Miller and Kettela 1975). One approach on the late developing spruces is to delay spray treatment until buds have flushed, but with high budworm populations, unacceptable loss of foliage in the bud stage may result. But, there is an earlier spray timing that can also be used. Insects on red spruce and black spruce that complete needle mining, find tight buds that they cannot enter until some swelling has occurred. These insects may remain in silken tubes on the surface of buds (Mott 1963, Hansen and Dimond 1982) or among clusters of previously mined needles (Varty and Godin 1983), and are exposed to sprays.

A split application is recommended for these spruces. The first should be when larvae are at peak L3 on spruce, and would correspond to midway between L3 and L4 on fir. The second should occur after bud flare on the trees, peak L5. Some applications, based on this sequence, have failed on spruce (Varty and Godin 1983) possibly because the second application was made too early, with spruce buds barely broken and larvae well protected. Often there is strong pressure and momentum to complete a spray project as soon as possible once started. This may lead to the second applications being applied too early.

Where target forests are a mixture of fir and red or black spruce, the split timings for spruce will provide the best combined protection for both fir and spruces.

Insect Densities and Vigor of Host Trees

These two factors are related because the important component of budworm densities is the number of insects compared to the number and size of new shoots that will be produced, and trees in poor vigor produce less new growth. Thus, an insect-density threshold, used to determine whether or not to spray, needs to be reduced as host tree vigor declines.

When there are one or more insects per bud at L3, populations are considered extremely high, and loss of current foliage will be complete by L4 - L5. When populations number one for each 2 - 4 buds they are considered high and defoliation may be complete by L5 - L6. Lower populations will result in less than total loss of foliage.

Insect densities and tree vigor determine timing of applications because, under extreme population levels, unacceptable damage can occur, even on balsam fir, before the bud mining stage is completed and insects become exposed to sprays. In response to this problem, trials and operational spraying at 50 percent larval emergence in the spring and later at the L3 - L4 larval stage, were tried in Quebec in the mid-late 1970s, when budworm populations were very high (Randall *et al.* 1977). While these authors noted good results, several other trials were unsuccessful (Blais 1977, Blais *et al.* 1981). Blais concluded that applications upon larval emergence in spring were largely useless, and that two applications at L3 and L4 produced better results. If, in extremely high populations, an early application was made, this should be followed by two, for a total of three applications. Blais also suggested that at extremely high populations, foregoing treatment should be considered. Little foliage would be saved by spraying, and the high natural reduction in budworm numbers that accompanies years of peak populations may be lost. Spraying, to regain tree vigor, could resume the next year when population pressure on the trees would be lessened.

As with the spruces, multiple sprays are useful for fir protection when budworm numbers are extremely high. The first application should be at L3, in an attempt to reduce bud losses through mining. The second should be made when the insect is more exposed so as to reduce population numbers substantially.

Blais (1977) reported observations on densities of spruce budworm larvae related to the time when unacceptable damage occurred on balsam fir. He worked in four plots with early-instar larval densities of 19, 29, 95, and 118 larvae per 45 cm branch tip. In the two plots with lower populations, 25 percent defoliation occurred at peak L5 and 50 percent at peak L6. Clearly, if balsam fir were the only important target in these plots, a single application could be used and delayed until L5. In the other two plots, 50 percent defoliation occurred at peak L5 and L4, respectively. Here, split applications would be appropriate. One would hope to achieve a moderate population reduction at L3, reducing bud destruction, and a stronger population reduction with a second application at L4.

Forest Management and Insect Management Goals

For much of the period that budworm-infested stands have been sprayed, the principal goal has been to keep stands alive until they could be harvested. This helps lead to an even flow of

wood to mills and a regulated pattern of regeneration of stands. Mature stands, where further growth is a secondary objective, can be kept alive by protecting as little as 30-50 percent of the current foliage in each year of treatment. Here, somewhat later applications, either singles or doubles, are favored. Some foliage can be sacrificed in hopes of achieving greater kill of insects.

Presently, however, with much budworm mortality of trees and much salvage of wood having occurred, there is concern in some regions for future wood supplies. As a result, there is an interest in maintaining good growth rates in younger stands, which requires the protection of 60 to 80 percent of annual foliage growth. In this instance, an earlier application is recommended, and since this alone may not give high kill of insects, split applications are warranted.

The size of budworm outbreaks and the inability to treat entire outbreak areas, among other reasons, makes outbreak suppression with insecticides impossible. Management through spraying aims at reducing insect numbers sufficiently, and early enough, to keep the required amount of foliage (see paragraph above) on the trees for that growing season.

There have been a few, rare cases where attempts at outbreak suppression seemed feasible and gained, at least, temporary success (Blais 1973, Dimond 1976). These situations had the following in common: outbreak patches were discreet with clear boundaries; there were no outbreak areas to the west to provide re-invasion; it was possible to treat entire outbreak areas with a strong insecticide; it was possible to follow up with mop-up applications in the next year or two, if necessary. Declining budworm numbers or unfavorable weather for budworm survival may have contributed to success in these cases. Timing of suppressive treatments in these instances should be delayed to the later instars, with maximum mortality of insects the goal. Two, strong treatments should be applied for maximum benefit if different host species are involved and to avoid any gaps in the spray coverage.

Weather

Weather is a major concern in spray application; spray that does not reach the target is wasted. However, that topic involves application technology and not timing. Here we are assuming that all spray is applied under favorable weather. However, weather remains a factor in timing of application, directly and indirectly.

First, there is an interaction between weather and the spring development of both the budworm and its host trees. In a spring dominated by cool, rainy, cloudy weather, foliage of balsam fir develops relatively faster than the budworm, leading to large, expanding shoots sheltering very tiny caterpillars (Varty and Godin, 1982). Under these conditions, spraying can be delayed, without suffering serious damage.

If budworm populations are moderate, one can consider reducing spray acreage where trees are in good condition. With bright, sunny, warm spring weather, on the other hand, the relative phenologies are reversed, particularly if deep frost or snow is retarding tree development. In this instance, earlier spraying is called for.

Secondly, the weather following spray application should be considered, in addition to the weather during application. Treatment with either chemicals or B.t. perform poorly or fail when application is followed by several days of weather that produces inactivity in budworm larvae. The major factor is temperature, and there will be little budworm activity at temperatures of 10 - 15C. Air temperature is not the only factor. Direct sunshine can increase temperatures within budworm larval microhabitats well above air temperatures. Budworm activity is also reduced by rain or high humidity.

Varty and Godin (1982) make a useful distinction between the inner habitat and outer habitat of budworm larvae. The inner habitat is the needle mine or bud mine or silk tube or webbed shoots that a budworm larva constructs. Spray droplets do not penetrate the inner habitat. The outer habitat is encountered when larvae move from needles to buds or to shoots, when larvae feed on needle tips or bud surfaces or enter a needle, when larvae are spinning down on silk threads or constructing shelters. It is during these displacements that larvae will encounter spray droplets, and these occur only above threshold temperatures, and more frequently at high temperatures. If one must make a choice, it is probably preferable to spray in marginal weather, knowing the next few days will be sunny and warm, than it is to spray in ideal weather, knowing that a prolonged rainy, cloudy, cool period is approaching.

Associated Insects

Another insect often accompanies the budworm during outbreaks. This is the spruce coneworm, common to all spruces, but much less abundant on fir. Spies (1983) showed that, in Maine, 15 to 30 percent of the defoliators on spruce were coneworms rather than budworms. He showed that this relationship is persistent and that spatial and temporal variations in budworm and coneworm numbers have been parallel since the 1940's. It is known that, with some chemical insecticides, coneworm larvae survive spraying better than budworm larvae, and the majority of survivors on spruce may be coneworms (Nicholson and DeBoo 1976, Spies 1983). While we know that the phenology, feeding habits on spruce, and types of damage of the coneworm are very similar to the budworm, we know very little about the best timing of spray application for the coneworm. Yet, some failures to protect spruce with sprays may be as much because we failed to kill coneworm as failing to kill the budworm. We presently have no recommendations for increasing the effectiveness of sprays against the coneworm. The topic requires research.

Final Comments

What preceeds outlines an array of factors that should be considered in the timing of spruce budworm spray operations. However, decisions on timing will usually involve a series of compromises because sizeable spray blocks are a composite of varying insect densities, varying levels of tree vigor, and varying topography affecting insect and host development. For these and other reasons, few stands will be treated at the optimal time. Planning and striving for best timing, however, will reduce chances of failures.

Further research is needed on all aspects of timing of spruce budworm applications; but of particular note is the difficulty of obtaining reliably good results on spruce.

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AUTOMATED COUNTER FOR DETECTING AND
COUNTING EGG MASSES OF THE SPRUCE BUDWORM

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Abstract

An optical-electronic counter (Prototypes I and II) was designed and developed for detecting and counting egg masses of the spruce budworm and the western spruce budworm. The counter scans foliage samples, detects the presence of egg masses based on their characteristic fluorescing properties, and counts the egg masses electronically.

The spruce budworm, Choristoneura fumiferana (Clemens) (Lepidoptera: Tortricidae), is the most destructive forest insect pest in eastern North America. During epidemics millions of acres of spruce-fir forests are defoliated by larvae of this tortricid moth. Recorded outbreaks of the budworm date back to the early 1700's, but in the 20th century, outbreaks are increasing in frequency, extent, and severity (Blais 1983).

To determine spruce budworm population trends and predict damage levels, many Federal and State agencies spend tens of thousands of dollars each year sampling populations. The egg stage is routinely sampled because it is relatively stable (i.e., immobile) and offers an early warning signal of potential changes in population density. However, egg sampling is the most time-consuming aspect of population work (Morris 1955). Collecting samples of host-tree foliage is difficult and requires specialized equipment, such as extendable pole pruners with clamping devices (Morris 1955; Stein 1969). Once collected, the branch samples are examined for egg masses in the laboratory by trained examiners (Dixon et al. 1978), but the examination process is extremely tedious, time consuming, and subject to human error. Examination accuracy is related to budworm population level, the nature of the foliage, and worker experience (Morris 1951, 1955). Because of these difficulties, Morris (1955 p. 240) stated that the greatest need in the further development of sampling techniques for defoliating insects is for some purely mechanical, chemical, or electrical process for measuring insect abundance on a given quantity of foliage.

This paper describes the design and development of a machine that automatically detects and counts egg masses of the spruce budworm. The counter scans samples of host-tree foliage, detects the presence of egg masses based on their characteristic fluorescence, and counts the egg masses electronically.

Discovery of Fluorescence. -- Egg masses of some coniferophagous budworms fluoresce when excited by longwave ultraviolet (UV) light. The initial discovery of fluorescence (Jennings 1968) was made with the jack pine budworm, Choristoneura pinus pinus Freeman, which lays its eggs on needles of jack pine, Pinus banksiana Lamb. The excitation wavelength extends from 300 to 400 nanometers (nm). Initially we sprayed samples of jack pine foliage with a 0.05-percent solution of Fluorescein in 95-percent ethanol. However, we subsequently found that egg masses fluoresce naturally under blacklight (F40BLB lamp) without treatment.

Improving Accuracy and Efficiency of Foliage Examinations. -- After discovering egg-mass fluorescence, we designed a test to determine if accuracy and efficiency of foliage examinations could be improved by examining branches under blacklight. Samples of jack pine foliage were examined by four technicians under both blacklight and daylight, with examination order reversed for half of the examiners. The time required to examine each branch and the number of egg masses found were recorded. Results showed that blacklight significantly increased the accuracy of count and three of the four examiners found egg masses significantly faster ($P = 0.05$) under blacklight than under daylight (Jennings 1968). Most masses missed under blacklight were either parasitized or laid the previous year or years (i.e., old).

Additional tests with the western spruce budworm, Choristoneura occidentalis Freeman, and egg masses on Douglas-fir, Pseudotsuga menziesii var. glauca (Beissn.) Franco, foliage showed that egg masses were found more quickly (48% faster) and accurately (22% more egg

¹The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable. This Study is part of the Canada/United States (CANUSA) Spruce Budworms Program.

masses) with longwave UV light than with visible light (Acciavatti and Jennings 1976). Again, most egg masses missed under UV light (89%) were old and parasitized, whereas almost half of those missed under visible light (42%) were new. Morris (1955) indicated that the proficiency of inexperienced examiners is low; they may miss over 50% of the egg masses.

Design and Development of Prototype I. -- In 1976 a study was initiated at the University of Maine, Departments of Physics and Astronomy, Electrical Engineering, and Entomology, in collaboration with the Northeastern Forest Experiment Station to: 1) determine the fluorescence properties of spruce budworm egg masses, 2) determine the fluorescence properties of associated components on balsam fir foliage, and 3) determine the feasibility of using these properties to design and build a machine that scans foliage samples, detects egg masses, and counts the egg masses electronically.^{2,3}

A Turner® model III filter fluorometer was used for measuring fluorescence of spruce budworm egg masses and associated components on balsam fir foliage. This fluorometer has a high-pressure mercury arc lamp. A 7-60 filter was used to pass light (ca. 365 nm); the transmission band of this filter extends from 300 to 400 nm and corresponds to the long wavelength UV light used in previous studies (Jennings 1968). Different colored detector filters were used to study fluorescence; preliminary measurements indicated that violet (47B + 2A) and green (58) filters were the most useful. Background fluorescence levels were measured before and after each series of samples.

Results of spectral analyses with the Turner fluorometer indicated that egg masses of the spruce budworm have a characteristic violet and green fluorescence that is distinguishable from most other fluorescing components on

balsam fir foliage.⁴ Egg mass fluorescence shows activity predominately in the violet region, but the ratio of green to violet fluorescence is also important. By measuring levels of fluorescence and calculating ratios of green to violet fluorescence, egg masses of the spruce budworm can be distinguished from other fluorescing objects (e.g., buds, pitch droplets) on balsam fir foliage.

A prototype illumination and detection system was then designed and constructed. Basic components of the system include: a GE® 100 watt AC mercury arc lamp for source illumination; a highly transparent quartz lens for focusing the UV light source onto the sample; an adjustable field stop (0.7, 1.0, 1.4, or 2.0 mm diam.); two RCA® 8053 photomultiplier tubes (PMT) for detectors; a high-voltage power supply; and blue and green dichroic color filters for filtering light to the PMT's. The adjustable field stop allows for a point-to-point scan of foliage.

Tests of the prototype illumination and detection system confirmed that egg masses of the spruce budworm have characteristic fluorescence that is distinguishable from most other foliage components. With the prototype system, fluorescence levels no longer depend on object size; objects can be scanned point by point (2 mm). The brighter lamp, dichroic beam splitter, and sensitive detectors enabled detection and measurement of large signals (0.1 to 1 volts) for egg masses.

A conveyor belt with variable motor-speed drive was added to the prototype system housed in a light-tight chamber with entry and exit ports. Branch samples are placed on the conveyor belt, passed beneath the scanner-detector system, and discharged at the other end. A rotating mirror images and sweeps the UV spot (2 mm) across the foliage as the foliage passes beneath the scanner-detector system.

In cooperation with the University of Maine, Department of Electrical Engineering, and the Maine Forest Service, the Prototype I

²Cooperative Research Agreement 23-824, U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, and the University of Maine, College of Arts and Sciences, Department of Physics; A Prototype of a Spruce Budworm Egg Mass Counter; 1976. 6 p.

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⁴Carniglia, C.K.; Jennings, D.T.; Simmons, G.A.; Olsen, E.T. Investigation of the fluorescence properties of balsam fir foliage for the purpose of building an automatic spruce budworm egg mass counter. Final Rept., Cooperative Research Agreement 23-824. Orono, ME: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, and the University of Maine, College of Arts and Sciences, Department of Physics; 1977. 49 p.

egg-mass counter was tested in 1979.⁵ Branches were first examined using the machine (electronic counts) and then by human observers (manual counts). Records were kept of processing time, numbers of egg masses found, and foliage conditions. Efforts were made to collect and test foliage with low, medium, and high egg-mass densities.

Results of Prototype I tests indicated that, when calibrated, manual counts can be predicted ($R^2 = 0.97$, $\alpha = 0.01$) from electronic counts. And, electronic counting showed a highly significant ($\alpha = 0.01$) reduction in processing time. Manual examinations required a mean of 29.5 minutes per branch, whereas electronic examinations required only 8.6 minutes per branch. The mean difference of 21 minutes per branch represents a considerable savings in time and costs when large numbers of branch samples are examined. A patent (U.S. Patent 4,390,787) was applied for and granted to the inventors of Prototype I (Jennings et al. 1983).

Design and Development of Prototype II. -- A new egg-mass counter (Prototype II) is currently being designed and developed at the Forest Service Missoula Equipment Development Center, Fort Missoula, Montana. New design features include: a variable optical scanning system to detect fluorescence of both spruce budworm and western spruce budworm egg masses; programmable "windows" for setting maximum-minimum detection levels and for screening fluorescing components on five host trees (balsam fir, spruce, Douglas-fir, white fir, and grand fir); a stepper motor with variable belt-drive system; and a programmable microprocessor for operation and maintenance. Prototype II also has an "egg hunt" routine for scanning foliage until an egg mass is found, stopping, and then allowing the operator to view what the machine "sees." Field test of Prototype II is expected in 1984.

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A very rapid, simple, and highly sensitive assay for measuring the release rates of pheromones from insect lures involves the use of cold traps and analysis of the trapped pheromone based on the bioluminescence response of luciferase to long chain aldehydes. The assay is highly reproducible and trapping times as low as 5 min can be used. The sample need only be dissolved in water at room temperature and then injected into the luminescence assay. The release rate of 1 lure can be measured in less than 30 min requiring only a few minutes of the investigators time and permitting the routine processing of a large number of samples.

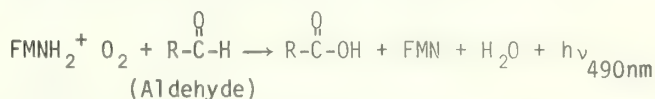
Introduction

Insect lures containing pheromone formulations are useful as attractants in monitoring and/or controlling insect populations. One of the important factors in interpreting the insect response to the lures is knowledge of the release rates of pheromone under different laboratory and field conditions. Variation in release rates of pheromones from lures will depend upon not only environmental conditions such as wind velocity and temperature, but also on the age, storage conditions, composition and design of the lure (Bierl-Leonhardt 1982; Daterman, 1982). In addition, measurement of the release rate of pheromone lures in the laboratory, can be affected by such factors as the design of the instrumentation (release chamber), the method of trapping the airborne pheromone or measuring its loss from the lure, the degree of sample manipulation, and even the method of analysis. It is also necessary to know the variability in release rate from one lure to another within a batch of insect lures so that the extent of variation in trap catches can be analyzed. Such differences in lure release rates may only be evident under specific conditions such as short (or long) storage of the lures or more extreme environmental conditions. In these latter cases, the information is valuable in terms of deciding the conditions of storage and how, when and for how long these lures should be used under field conditions. Unfortunately, most of this data is generally unavailable for insect lures. The absence of a standardized

system for measuring the release rates of lures and the effect of these different factors has turned an apparently simple problem on the surface into a situation where the comparison of lure release rates between different analysis systems and laboratories cannot be conducted in many cases with any degree of confidence.

The most common method for measuring the release rate of pheromones from lures involves trapping the released pheromone on a solid absorbent, followed by gas chromatography and analysis by flame ionization detectors (Byrne et al., 1975; Baker et al., 1980; Cross et al., 1980). However, this method is slow, requiring relatively extensive manipulation of the sample and limits the number of analyses that can be performed. Furthermore, agreement between the release rates of pheromone lures measured by gas chromatography and other techniques has not been clearly established particularly with lures containing less stable chemical formulations. For example, the release rate of gossypure measured by gas chromatography is much lower than that observed by direct release of radioactivity from a ^{14}C -labelled pheromone formulation (Weatherston et al., 1981).

Recently, we have shown that aldehyde pheromones can be detected at very low levels in a luminescence coupled system (Meighen et al., 1982; Grant et al., 1982). In this assay, bacterial luciferase catalyzes the oxidation of the aldehyde to the corresponding fatty acid in the presence of FMNH₂ and O₂ resulting in the emission of light as shown below.



As the analyses is conducted in aqueous solution, it is possible to use simple cold traps to collect airborne pheromone and analyze the trapped pheromone directly in water without further manipulation of the sample (Meighen et al., 1983). The luminescence response is proportional over a wide range to the amount of aldehyde injected into the assay and since maximum luminescence is reached in less than a second, analysis is extremely rapid.

The bioluminescent system can be used to measure different aldehyde pheromones even if they contain cis and/or trans double bonds with optimal response to chain lengths of thirteen to sixteen carbons (Meighen et al., 1982). Amounts as low as 20 pg of the aldehyde pheromone of the spruce budworm (trans-11-tetradecenal (96%) and cis-11-tetradecenal (4%)), Sanders and Weatherston, 1976) have been detected.



trans-11-tetradecenal



cis-11-tetradecenal

Consequently it has been possible to measure the daily rhythm of pheromone release and the rise and fall in pheromone levels in the glands of individual female moths (Morse et al., 1982). Other insect pheromones can easily be analyzed including those from such destructive insect pests as the tobacco budworm, the corn earworm and the navel orangeworm (Grant et al., 1982). By enzymic conversion of fatty alcohols and acetate esters to the corresponding aldehyde before luminescence analysis (unpublished experiments) the bioluminescent assay can be extended to a wide range of other insect pheromones.

The present report focuses on the analysis of release rates of insect lures using a combination of cold traps and luminescent analyses (Meighen et al., 1983). As the assay is highly sensitive, trapping need only be conducted for 5 min for a single lure, and analysis requires only a few minutes of the investigators time.

The release chamber and trapping system outlined in Figure 1 is a simple, inexpensive and very rapid method for collecting pheromone released from various emitters including insect lures. In this system, the lure is placed in a 16 mm glass tube about 8 cm from the outlet (Fig. 1). Air prefiltered through Porapak is dispersed by the glass wool to give laminar airflow and then passed over the lure. The pheromone is trapped by passage of the air through two 20 ml vials maintained at below -20°C . Trapping can only be conducted for periods of 1 hour or less since the build-up of ice in the apparatus will decrease the flow rate at longer times.

Water (~9 ml), part of which is used to rinse the short inlet tube, is added to each vial containing pheromone and ice (~1 ml), the sample is then vortexed for 10 sec and equilibrated at room temperature for 10 min before 1.0 ml aliquots are analyzed in the luminescence assay.

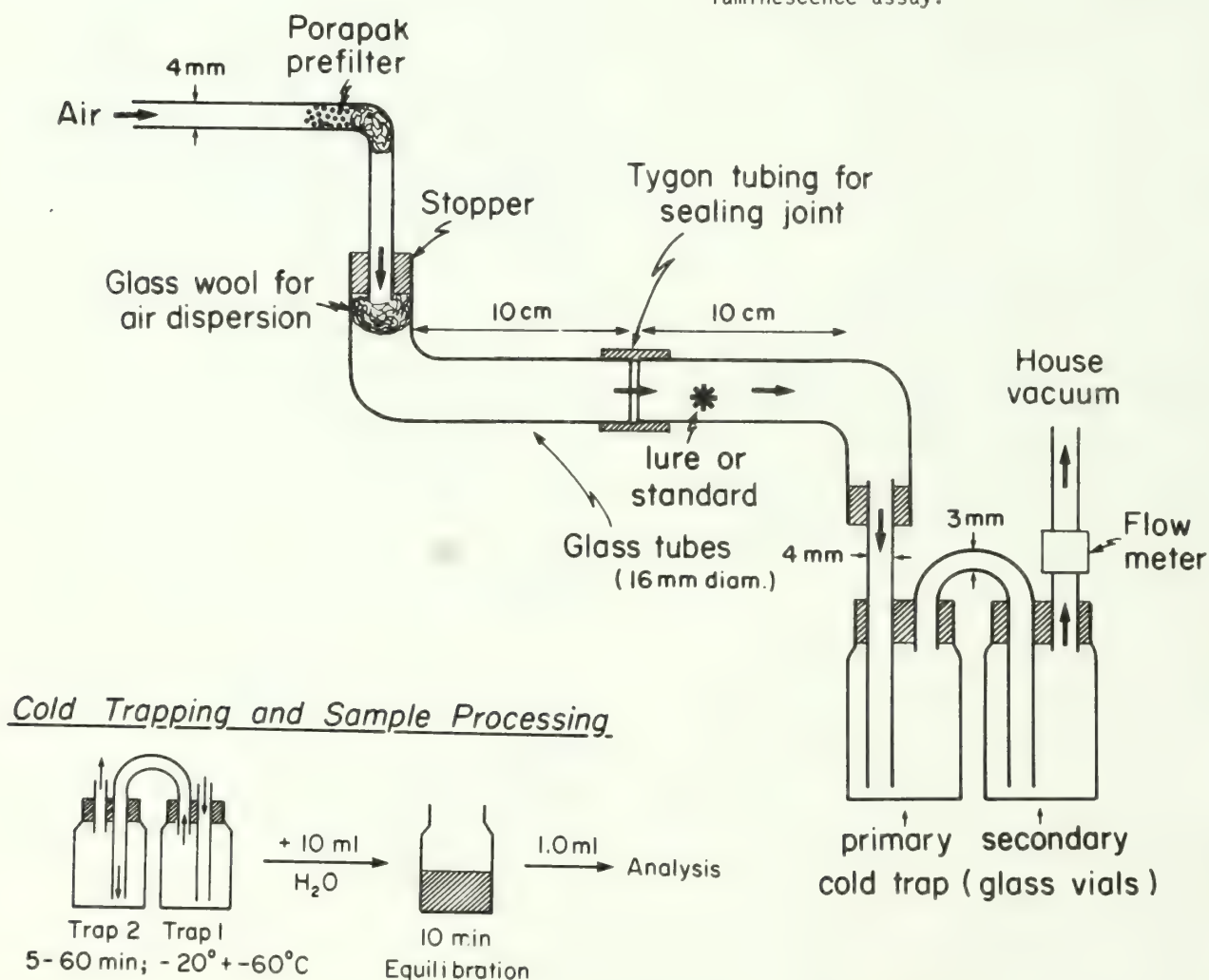


Figure 1. Release chamber, cold trapping, and sample processing for measurement of the release rates of pheromone lures.

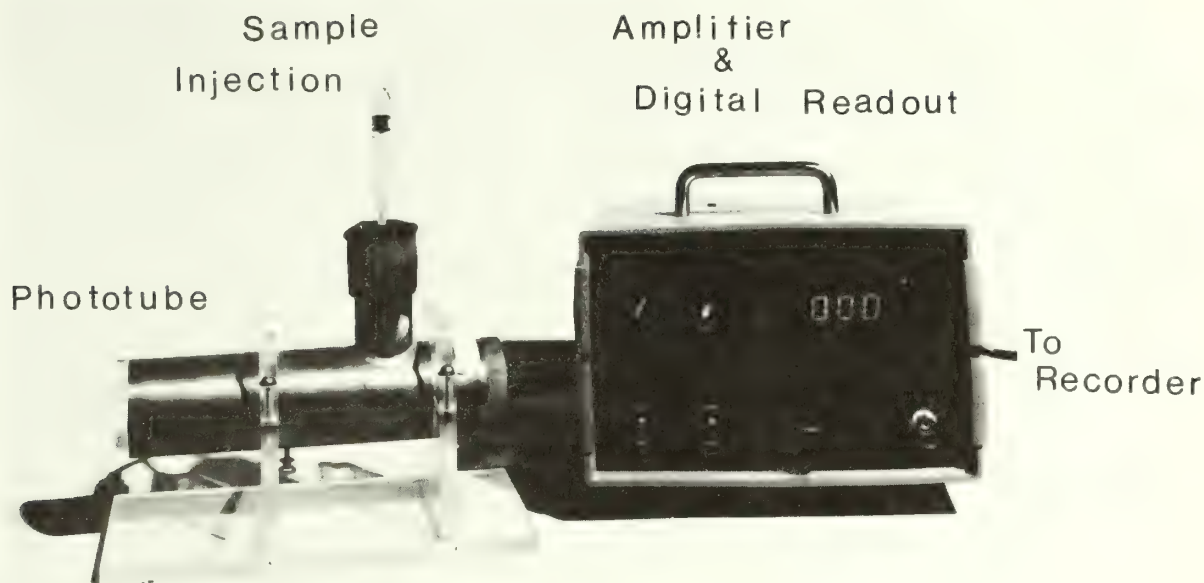


Figure 2. Equipment for the bioluminescence analysis of aldehyde pheromones.

Bioluminescence Analyses of Aldehyde Pheromone

Aldehyde pheromone in water (1.0 ml) is injected by syringe into 1.0 ml of assay medium contained in a 20 ml vial which has been placed in a light tight chamber and exposed to a photomultiplier tube (Fig. 2). The assay medium contains 0.001 M NH_4OH , 0.05 M β -mercaptoethanol, 0.05 M Na/K phosphate, pH 7.0, and 50 μM flavin mononucleotide (FMN). A constant amount ($\sim 5 \mu\text{g}$) of bacterial luciferase (10 μl of a 0.05% solution) is added to the assay medium followed by a small excess ($\sim 0.5 \text{ mg}$) of sodium dithionite (Meighen & MacKenzie, 1973) to reduce the FMN (yellow) to FMNH_2 (clear) just before injection of the aldehyde pheromone. Stock solutions of luciferase (10 mg/ml) were purified from the luminescent bacterium, *Vibrio harveyi* (Gunsulus-Miguel et al., 1972) and can be stored for at least 2 years in 35% glycerol at -20°C without loss of activity. Enough enzyme is obtained from 10 liters of bacterial culture to conduct over 10,000 assays. Secondary luciferase stocks (0.05%) are prepared by dilution (1:20) of the stock 1% luciferase into 0.05 M β -mercaptoethanol, 0.05 M phosphate, pH 7.0, at 4°C and used within a period of 2 to 3 days.

Light emission is detected by a photomultiplier tube, amplified and the maximum emission is either recorded graphically or on a digital readout. Figure 3 illustrates the response to 21 ng of the trans and cis isomers of 11-tetradecenal, the pheromone components of the spruce budworm. The maximum luminescence (in light units, LU) is directly proportional to the amount of a specific aldehyde pheromone over a wide range (0.2 - 500 ng).

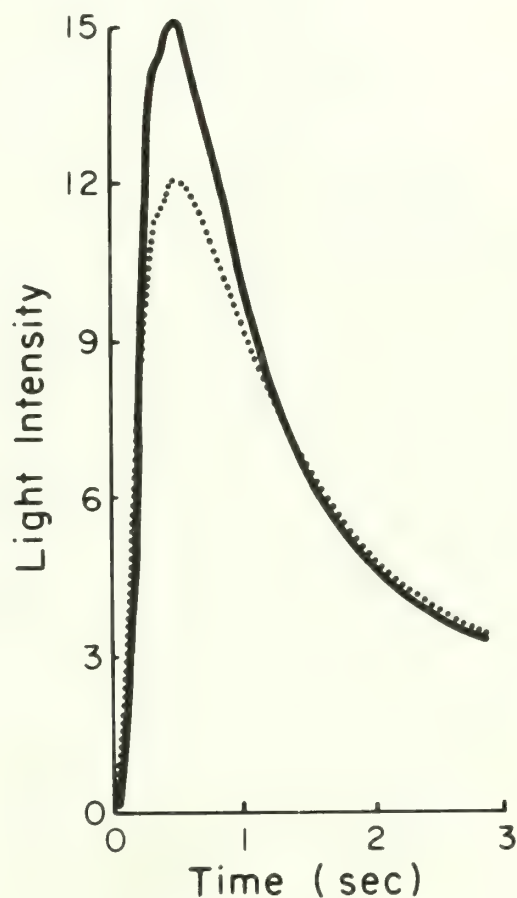


Figure 3. Luminescent response to 100 pmol of trans-11-tetradecenal (—) and cis-11-tetradecenal (....).

TABLE 1

Release Rates of Pheromone Lures

Lure ^a and Storage Conditions	Age	Trapping/Analysis System ^b (airspeed)	Release Rate ^c µg/day
Fiber	2	Cold Trap/Biolum.	3.7
Z-9-C ₁₆ -al	4	(0.4 mph)	1.8
0.4 mph	2	Porapak/Radioact.	3.6
	4	(0.4 mph)	3.8
3% PVC	5	Cold Trap/Biolum.	48
Still Air	30	(2 l/min)	31
	60		20
0.3% PVC	5	Cold Trap [Porapak]	4.0[2.4]
Still Air	30	Bioluminescence	2.2[1.5]
	60	(2 l/min)	1.3[1.4]
Fiber[1 mph]	6	Cold Trap/Biolum.	5.0[2.2]
Still Air	40	(1 mph)	2.4
Flake[1 mph]	6	Cold Trap/Biolum.	0.83[0.8]
Still Air	40	(1 mph)	0.40

The combination of cold trapping and bioluminescence analysis leads to a very rapid and sensitive method for measuring the release rates of pheromones. The efficiency of recovery of pheromone in the trapping system is not only high, but reproducible from one analysis to another. Using a fixed amount of trans-11-tetradecanal in the release system, an average of 69% of the pheromone was collected in the first trap on analysis of 40 control samples over a period of two months with a standard deviation of only 7%. Consequently, only the amount of aldehyde in the first trap needs to be measured for routine processing of samples without taking into account the level of pheromone ($\approx 16\%$) in the second trap. For example, if 1 µg of trans-11-tetradecanal or cis-9-hexadecenal are placed in the release chamber, luminescence responses of 35 LU and 24 LU, respectively, will be obtained on analysis of a 1.0 ml aliquot from the first trap corresponding to 10% of the sample. The luminescence response is proportional to the amount of a particular aldehyde pheromone and is limited by the background response (no added pheromone) which is approximately 0.04 LU under these trapping and assay conditions. Thus even amounts as low as 4 ng can be released in this system (in < 1 hour) and then detected on analysis of only 10% of the trapped sample. The lower limit of pheromone release capable of being measured in this system is therefore ~ 0.1 µg/day.

Table 1 gives the release rates of a number of different pheromone formulations. A direct comparison of the release rates measured by two completely different systems was accomplished by using a lure containing [1-¹⁴C]cis-9-hexadecenal and analyzing the amount of radioactivity released and the bioluminescence response to trapped pheromone. In order to obtain sufficient radioactivity, trapping had to be conducted for 20 hours whereas only 30 min trapping was needed for the cold trap bioluminescence system. Excellent agreement in release rates between these two systems was obtained for 2 day old lures whereas a lower rate ($\sim 50\%$) was obtained in the luminescence system for 4 day old lures possibly reflecting some degradation of the ¹⁴C-labelled pheromone. In a similar study in another pheromone release system (Weatherston et al., 1981), the amount of radioactivity released in a flow system was over 18-fold higher than the amount of pheromone released determined by gas chromatography. The closer agreement between the amount of radioactivity released and the luminescent response may reflect the very short times required for analysis in the luminescent assay and the low temperature of the trapping system which minimizes any degradation of the pheromone.

The release rates for PVC, fiber, and flake lures containing the spruce budworm pheromone formulation are also shown in Table 1. A decrease in rate of release of pheromone is

^aAll lures contained the spruce budworm pheromone except for the first fiber lure which consisted of [1-¹⁴C]-cis-9-hexadecenal (courtesy of M. Golub, Conrel). Polyvinyl chloride (PVC) lures (130 mg) containing 3% and 0.3% by weight of pheromone were received courtesy of Dr. C. Sanders, Great Lakes Forest Research Centre, Sault Ste Marie. Fiber lures (1.25cm; ~ 0.1 mm, i.d.) containing ~ 60 µg of pheromone were from Conrel (Albany Int.) and flake lures (1cm²) containing ~ 500 µg of pheromone were from Hercon (Herculite Products). The temperature for storage and release was 21°C.

^bTrapping on Porapak Q and bioluminescence analysis was conducted as described by Szittner et al (1982). For radioactivity analysis, trapping was conducted for 20 to 22 hours to obtain sufficient counts (~ 10 cpm per hour) and the Porapak extracted into the scintillation cocktail (Econofluor).

^cThe values in square brackets refer to the indicated changes in storage or trapping of the pheromone lure.

observed on storing the lures at 21°C with a half time of about 30 days for all three lures. The variation between individual lures of the same type and batch are relatively low ($< 20\%$ S.D. after 20 days) providing the age and storage

conditions are identical. Changes in the storage conditions will affect the release rates of the lures (Sanders, 1981) with the relative effects being dependent on the severity of the conditions, and the age and type of lure.

The release rates for the PVC formulations are in excellent agreement with the values reported by Sanders (1981) based on weight loss measurements. For example, after 40 days of equilibration, release rates of 25 $\mu\text{g/day}$ and 0.5 $\mu\text{g/day}$ based on weight loss were obtained for the 3% and 0.3% formulations, respectively.

The large effects of wind velocity and temperature on the release rates of pheromone from the fiber and flake lures are shown in Table 2. A decrease in wind velocity of 10-fold

TABLE 2

Dependence of Pheromone Release Rates
On Wind Velocity and Temperature

<u>Conditions</u>		<u>Release Rate^a</u>	
Wind Velocity (mph)	Temperature (°C)	Fiber	Flake
1.0	21	100	100
0.4	21	60	80
0.1	21	10	20
1.0	31	300	400
1.0	15	80	90

^aPercentage of release rate at 21°C and 1 mph measured by the cold trap/bioluminescence system for fiber and flake lures containing the spruce budworm pheromone.

causes a drop in the release rate of 5 to 10-fold depending on the type of lure. Similarly, an increase of 10°C in the temperature results in an increase of 3- to 4-fold in the rate of pheromone release. The relative effects of changes in the temperature and wind velocity on release rates have been found to be dependent on one another to some degree. These effects may also be dependent on the past history (age and storage conditions) of the lure.

Knowledge of the release rates of insect lures and the effects of different factors on pheromone release is important for their effective use in controlling and/or monitoring insect populations under field conditions. A standardized system for comparing the release rates of lures from one laboratory to another

and between different lures is essential. The cold trap-bioluminescence system has the sensitivity, reproducibility and speed for routine and rapid analysis of a wide range of insect lures.

Acknowledgements

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Abstract

Traps baited with the sex pheromone of the spruce budworm provide the forest manager with an inexpensive, efficient method of monitoring changes in budworm populations even at low densities. Comparison of catches from year to year indicates population trends and provides early warning of outbreaks. Correlations between trap catch and population density suggest that sex pheromone traps can supplement, or even replace, other more costly sampling techniques as indicators of absolute density. Comparability of catches from year to year is affected by many factors. Some, such as climate and stand conditions are uncontrollable, but can be allowed for. Others, such as trap and lure design have been the subject of considerable research and the necessary attributes have been defined. Field tests are in their final phases to determine the best available commercial designs for a coordinated operational program throughout northeastern North America.

Historically, management of North American forests to cope with insect pests, such as the spruce budworm (*Choristoneura fumiferana* Clem.) has been carried out with only a short-term horizon; action is taken only when trees are about to die, and then it is limited to accelerated harvesting, salvage cutting or to the application of insecticide to kill enough insects to protect the foliage and keep the trees alive.

This situation is largely a reflection of the level of forest management in North America; investment in the growing stock is minimal, inventories are inaccurate and out of date and growth and yield data are sketchy. But this situation is changing. As the resource becomes increasingly depleted, more intensive management will be essential if the supply is to be maintained. Not only will this necessitate more detailed and accurate inventories and better predictions of growth and yield, it will also require more accurate estimates of losses due to insect and disease, and more accurate predictions of where and when the losses will take place, so that remedial action can be planned well in advance.

Our knowledge of budworm population dynamics has not yet reached the point where we can predict outbreaks with any accuracy, but our understanding is improving. Even now, it may be possible to provide much more advanced warning than was available in the past.

Between outbreaks spruce budworm numbers can drop to extremely low values, lower than many of the other associated defoliating insects. For instance, during the period 1961 to 1965, 800 branch-samples were collected from host trees in northwestern Ontario each year--a total of 4000 branches during the 5 years, but in that time only 3 spruce budworm larvae were found, less than 1 per 1000 branches. Similarly low population densities were recorded by Miller and McDougall (1966) in the early 1960s in northern New Brunswick. Given such low population densities how can we detect the beginnings of the next outbreak?

Conventional sampling using pole pruners is not practical at these densities. The generally accepted threshold density at which it provides meaningful estimates is 1 larva/branch. This level represents a 1000-fold increase over the densities recorded between outbreaks, and may already be too late for preventative action to be taken. Beating-mat samples, long in use by the Forest Insect and Disease Survey Branch of CFS, although easier to obtain than branch samples, suffer the same problem; large numbers of samples are required to reflect changes in population density when populations are sparse (Miller et al. 1968).

The alternative is the use of sex pheromone traps. When ready to mate, female moths of nearly all species release chemical blends which act as a signal and guidance system for the male moths. These sex pheromones are highly potent and species-specific, and are extremely effective in luring male moths to traps. They are now in use or under development for the detection and monitoring of numerous species. Their advantages are their species-specificity (only the target insect is captured in contrast to light-traps) they are inexpensive, easy to use and very efficient. In northwestern Ontario when populations were extremely low in the 1960s traps baited with virgin female spruce budworm, caught an average of 19 males/trap in one year, while Miller and McDougall (1973) caught 152 males over a 2-yr period in 25 traps when populations were extremely low in the early 1960s in northern New Brunswick.

To be successful a sex pheromone trapping system requires 3 basic ingredients, 1) a potent attractant, 2) a formulation for protecting the attractant from degradation and which releases the attractant at a constant rate, and 3) a suitable trap design.

The chemical composition of the spruce budworm pheromone has been identified (Sanders and Weatherston 1976; Silk et al. 1980). There is some evidence that some minor components are missing (Sanders 1984a), but as a lure the known blend [(E)- and (Z)-11-tetradecenal in a ratio of 95(E):5(Z)] is as effective as a virgin female moth (Sanders 1981) and it is unlikely other ingredients will make any major difference.

Four formulations have been tested and found adequate for dispensing the pheromone (Fig. 1). The solid polyvinyl chloride formulation has been used for many years and has been tested extensively (Sanders 1981; Meighen et al. 1983). The Hercon plastic laminate chip and the Albany International (Conrel) hollow fibre have also been widely used both in Canada and the U.S. (D.C. Allen and cooperators pers. comm.). The Bend encapsulated formulation has not been widely tested yet. The important criteria are that the pheromone should be released at a constant, specified rate, that there is little variation among the lures in any one year or from year to year. A release rate in the range of 20-100 ng/h has been selected as the required release rate, which is relatively low and creates some problems for the formulators. Further testing is required before a 'best' dispenser is decided on, probably all four will eventually prove equally suitable; the final choice may be one of cost.

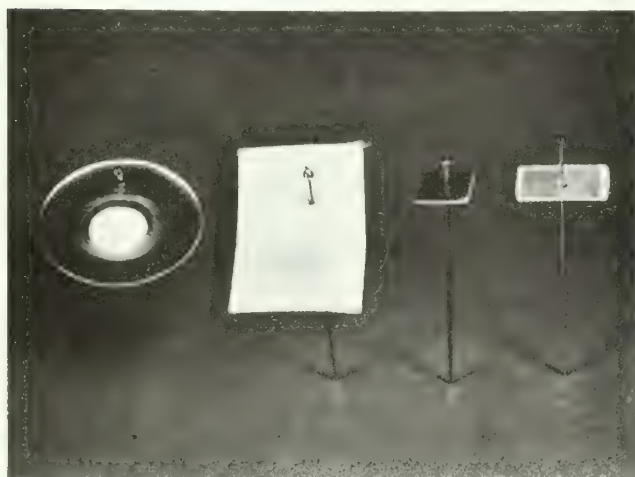


Fig. 1. Formulations for dispensing insect sex pheromones. L-R. Bend capsule, Albany International (Conrel) hollow-fibre (mounted on paper backing), Hercon plastic laminate, polyvinyl chloride (PVC) pellet.

The major variable which has been investigated, both by us in Canada and by CANUSA sponsored researchers in the U.S., is trap design. Initially, sticky traps were used, which have been in common use for many lepidopterous pests for several years, and the Pherocon LCP was selected as the best suited for monitoring the spruce budworm (Sanders 1978). However, such traps have only a limited capacity before the sticky surface becomes covered by moths and wing-scales, limiting their ability to catch more moths. The 'saturation point' of Pherocon LCP traps is about 50 moths/trap, a point which is reached quite quickly even with low potency lures when population densities exceed 1 larva/branch (Houseweart et al. 1981). If the traps are to be used only as an

early warning system, then trap saturation could be taken as the threshold value for more detailed sampling using more conventional sampling methods. However, Ramaswamy and Cardé (1982) found that funnel traps were probably as effective as the sticky traps at low densities, but with the advantage that they could be used over a much wider range of population densities. This raises the possibility that sex pheromone traps could be used to provide accurate, quantitative estimates of population density, so replacing other sampling techniques, instead of just extending our ability to monitor low density populations. A number of such 'non-saturating' traps are now available (Fig. 2). All operate on the same principal; the pheromone lure is placed inside the trap, together with a piece of plastic, impregnated with dichlorvos (such as Vapona, Fly-tox or No-pest strips) to kill the trapped insects. The question to be answered now is which trap design is best suited for our purpose. It is important that we make the right decision now, before an extensive, long-term trapping program begins, because changing trap design in the middle will necessitate re-calibrating the trap-catches against population density, and will make long-term trend analysis meaningless, or difficult to interpret.

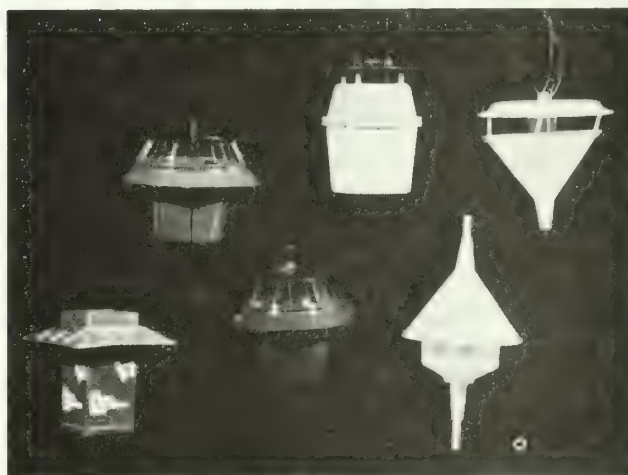


Fig. 2. Six designs of non-saturating, non-sticky traps tested for monitoring spruce budworm populations. top, L-R. Health-Chem plastic canister, International Pheromones Ltd. Uni-trap, Covered funnel trap. Bottom, L-R. Health-Chem milk carton, Baker Chemicals Bag-a-Bug, Double funnel trap.

One measure of a trap's suitability for estimating population density is to see how well trap catches correlate with other estimators of population density over a wide range of densities. Such correlations have now been gathered in a number of places for a number of years (Ramaswamy et al. 1983; Allen and cooperators, pers. comm.; Sanders 1984b). Regression coefficients (r^2) range up to

, indicating beyond doubt that sex pheromone traps do have potential for estimating population density. Most of this work has been done with 'membrane' traps, the covered funnel trap or the double funnel trap (Fig. 2).

For standardization of an operational system requiring many different jurisdictions, there is considerable merit in using a readily available commercial trap. Attention has now turned to evaluating these. Two traps marketed by Health-Chem for gypsy moths, the milk carton and plastic canister trap (Fig. 2) were used with or modifications in a number of trials in 1983 carried out in Canada and the U.S. In some instances regression coefficients were quite high, observations by a number of cooperators on moth behaviour coupled with low catches (Allen et al. comm.) raised questions about suitability of designs for trapping spruce budworm moths. In earlier trials variation in catch among traps was high, a feature which suggests catches may be unreliable.

Recently we have made observations on trap performance in a wind tunnel. The first test was to determine how long a moth had to remain inside the trap to be overcome by the dichlorvos residues. Moths were placed in a jar with the standard-sized piece of dichlorvos plastic strip and the time taken before the moths became incapacitated was recorded. The experiment was repeated with strips of different age to see if effects were slower as the strip aged. The results were as follows:

Age of insecticide strip (weeks)	Average time to incapacitate moths (min.)
0	2.06
1	3.13
2	4.00
3	4.42
4	6.52

Figure 1 shows that there is an aging effect, but that a figure of 5 min. is a reasonable estimate of how long a moth must remain in the trap to be considered 'caught'.

Each trap in turn was then hung in the wind tunnel, baited with pheromone. Moths were released one at a time in the pheromone plume and their subsequent behaviour recorded, whether they entered the trap, whether they escaped, and how long they remained inside for 5 min. Table 1 shows the results and includes the numbers of moths captured by each trap design in a low population of spruce budworm in the field in 1983. The largest numbers of moths entered the 2 trap designs which had the 'all round' openings (the CFT and IPL). However, the moths escaped from the CFT almost as fast as they entered, while in the IPL only 1 escaped out of 22 entering, a function of the inverse funnel shape of the trap acting as a barrier to escape. Moths also easily entered (but also easily escaped from) the milk carton trap. Numbers entering the

Table 1. Comparative performance of 6 non-sticky sex pheromone traps in a wind tunnel and in the field.

Trap design	Wind tunnel			Field
	Number* entering trap	Number* escaping	Number† remaining in trap	Number captured
International Pheromone	22	2	20	78
Health-Chem "carton"	17	15	4	3
Health-Chem "canister"	11	9	4	7
Bag-a-Bug	4	1	3	8
Covered funnel	21	17	7	26
Double funnel	14	5	9	39



* Within 5 min. period after release of moth.

† At end of 5 min. period, including those which escaped and re-entered.

other designs were lower, and observations showed that this was due to difficulties the moths had in locating the openings under the overhanging 'eaves' of the traps. Clearly the IPL trap is the most efficient in capturing the moths attracted by the pheromone in the wind tunnel. Furthermore, the wind tunnel data on the numbers remaining in the traps are in close agreement with the field trapping data, suggesting that the same factors are operating in both situations, implying that the wind tunnel tests are a valid indication of what may be expected in the field.

Also, during our wind tunnel observations, we recorded where the moths first contacted the trap as they approached upwind along the pheromone plume. The results (Table 2) were rather surprising. Initial contact was anywhere on the traps, from the tops to the very bottom. Only in the CFT and IPL traps did any moths contact the opening where the pheromone is being released.

Table 2. Percentages of male spruce budworm making initial contact on different portions of 6 non-sticky sex pheromone trap designs (shown diagrammatically).

	IPL	Can-ister	Car-ton	B-a-B	CFT	DFT
	0	3	13	13	4	21
	0	17	37	24	0	27
	4	0	0	0	14	0
	60	22	7	13	36	19
	36	58	43	50	46	33

This implies that the pheromone is not being emitted in a very clear cut plume, and this was checked out by releasing titanium chloride 'smoke' from the traps in the wind tunnel. The resulting 'plumes' corroborated the behavioural observations (Fig. 3). The in-filling of air around the down-wind side of the traps carries the pheromone with it. As a result the smoke appeared as a fog from those traps with the holes, much of it emitting from the side holes as well as those on the down-wind side, and the concentration appeared to be similar from top to bottom of the trap. By contrast, smoke from the CFT and IPL traps tended to appear in more of a plume, presumably because the airflow was smoother, with a distinct flow through the open area below the roof.

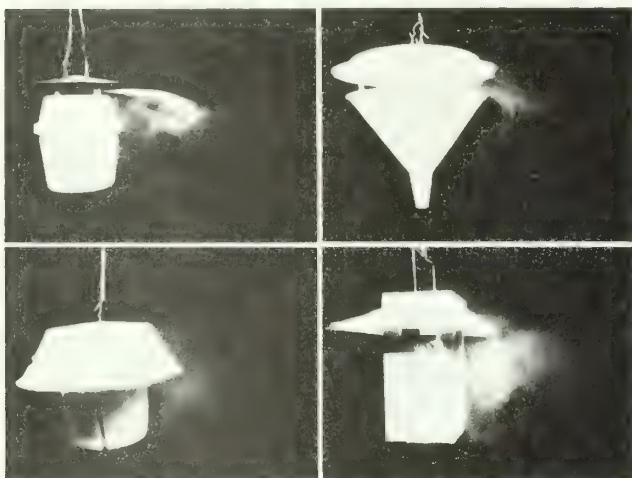


Fig. 3. Flow of titanium chloride fumes from pheromone dispensers in four non-saturating traps. Top L-R. IPL, Covered funnel, Bottom L-R. Health-Chem plastic canister and milk carton.

The important criterion by which to judge the suitability of a trap for population monitoring is not necessarily how many moths it catches, but how closely the catches reflect the true population density. Therefore the final trap choice must await data on correlations between trap catch and larval and/or egg densities. Nevertheless the fact that the IPL trap catches and retains most of the attracted insects is an important point in its favour. There are many factors which influence trap performance, some of these such as trap position, trap height and distance between traps can be standardized. Others, such as the effects of stand composition, temperature, and humidity cannot. Inefficient traps introduce yet another variable leading to variation in trap catch which should be avoided if possible.

Conclusion

Traps baited with the sex pheromone of the spruce budworm can provide information at several

levels of complexity for assisting in the long-term management of budworm-prone forests.

At the simplest level sex pheromone traps placed out in the same locations year after year can provide data for time-series analysis, using the catches as a comparative annual index of population density.

At the next level, knowledge of the relationship between trap catch and population density, would allow us to select 'thresholds', i.e. numbers where some further action, such as more detailed sampling, is required.

Finally, the establishment of correlations between trap catch and population density can provide the forest manager with another sampling tool which can supplement, or even replace, some of the sampling that is now done with more costly and time-consuming techniques.

For the first two, time series analysis and thresholds, the cheap and convenient sticky traps are suitable. For the third, quantitative estimates of population density, more expensive non-saturating traps are necessary. Although any of the non-saturating trap designs discussed here are probably adequate for this purpose, the fact that we are embarking on an extensive, long-term monitoring program requiring a standardized trap, means we must ensure that we have the best available trap for the purpose. By the end of 1984 we should know which this is.

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Spruce budworm and balsam fir forest simulation models are discussed. Both the MFRC/IRE and an improved "Maine" model suggest that the forest protection policy which has been used in Maine and New Brunswick is inferior to alternative low egg-density-threshold policies.

Introduction

Several studies of the spruce budworm in the spruce-fir forests of eastern Canada and Maine have been conducted using simulation models. A goal of these studies is the identification of cost-effective spraying strategies which prevent spruce budworm outbreaks from causing extensive tree mortality.

This report discusses the need for and usefulness of simulation models for evaluating the consequences of alternative management policies. The results of studies by Watt and lead by Askerville are presented. The structure and variables used in the Maine budworm-forest model are described and the Maine model is used to calculate the spraying frequency which results from alternative spray policies. Spray policies which suppress budworm populations before outbreak densities are reached and severe defoliation occurs appear to be superior to forest-protection policies. Forest-protection policies currently in use in Maine and New Brunswick spray only if tree health is threatened.

Why Use A Simulation Model?

Evaluation of the effectiveness of alternate spraying programs or policies is a difficult undertaking. An evaluation must account for many factors. Budworm survival is of particular importance. It is affected by:

- food availability
- budworm density
- insecticide applications
- parasite density, and
- prevailing weather conditions.

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Food availability is determined by the conditions of the host trees and their response to budworm feeding; the dynamic budworm-foliage relationship is central to understanding budworm population changes, tree-growth loss, and tree mortality.

Also a major concern to budworm-forest management are the consequences of moth dispersal between forested areas in Maine, Vermont, or New Hampshire and into those states from infestations in Quebec, New Brunswick, and other parts of New England. The possible spread of infestations which are not suppressed is an important management concern and the occurrence of moth influxes into an area from other areas complicates the problem.

To predict the probable behavior of the budworm-forest system under a particular management strategy, it is necessary to integrate our best scientific understanding of these processes and their interactions. Because of the complexity of this system, simulation models are best able to keep track of the important information and to represent the major interactions.

Budworm-forest simulation models discussed here are useful for predicting the average behavior of the budworm-forest ecosystem when a particular management policy is followed. For example, suppose the forest is managed to maintain a fixed harvest level. Suppose also that a site will be sprayed whenever tree mortality would commence the following year if the site were not sprayed. Then, via simulation, the average behavior of the forest can be determined.

Results With Earlier Models

An early simulation model for a forest insect pest was constructed by K.E. Watt (Watt, 1964). He considered a hypothetical 6.4 million-acre balsam fir forest which he divided into 625 sites, each of 16 square miles. Each site contained 8-inch diameter trees at a density of 265 trees/acre. To describe insect dynamics, Watt used Morris's Key-Factor relationship (Morris, 1963, p. 124) for spruce budworm survival which specifies that

$$\ln N_{t+1} = .98 + .76 \ln N_t + .18(T_{\max} - 66.5^{\circ}\text{F})$$

where:

N_t = budworm density in year t , and

T_{\max} = mean maximum temperature 1 June through mid-July.

Watt modified this relationship to account for parasite attacks, disease incidence and moth dispersal. Relationships were constructed for tree-growth loss and mortality as a function of previous defoliation. Watt examined the

release of parasites, viruses, and the use of insecticides as control measures. He concluded: "for all kinds of control, control is vastly more effective if applied 10 years or more before peak pest densities," (Watt, 1964). Though Watt's model is in some respects naive, subsequent work also has shown the advantage of early control action.

An active Canadian effort to develop a New Brunswick budworm-forest simulation model began in 1972. Early models are reported in Stander (1973) and Jones (1974, 1976). The last Jones model is the basis of the Report of the Task-Force for Evaluation of Budworm Control Alternatives (Baskerville, 1976). That model will be referred to as the Maritimes Forest Research Center/Institute of Resource Ecology (MFRC/IRE) model reflecting the institutions involved in its construction.

The task-force report uses a 450-site representation of New Brunswick's forest. The MFRC/IRE model mimics the survival of budworm populations in each site during five life stages: eggs, first and second instar, third through sixth instar, pupae, and adults. In addition, the response of the trees to budworm feeding is modeled by accounting for their production of new foliage and retention of old foliage.

The task-force report considers the impact of several policies on the forest and on the economic activities of the forest industry. The report considers three policy sets: no-control, historic-crop-protection, and preemptive control (Baskerville, pp. 139-164). (1) It is projected that if control operations were ended in 1976, the resulting budworm outbreak and continued cutting would deplete the forest's inventory by '1995' with no recovery until after '2025'. (2) The historic crop protection policy is shown to protect the forest from substantial mortality; but on average, 11.3% of the forest area must be sprayed each year. With this policy, the forest is frequently in poor condition because it is allowed to go to the brink of mortality before spraying occurs to provide relief. Deletion of areas to be harvested from the spray areas results in only a marginal decrease of 0.7% in the average area sprayed. (3) The preemptive strategies are the most promising. By spraying sites whose egg densities exceed 160 eggs per square meter of foliage, the average area sprayed is reduced to 7.3% of the forest. If the spray threshold is lowered to 86 eggs per square meter of foliage, then on average only 3% of the forest is sprayed per year. Again, early control action seems to be advantageous.

The Maine and MFRC/IRE Budworm-Forest Models

Before proceeding to a discussion of results derived with the Maine budworm-forest model (Stedinger, 1977), it is advantageous to discuss

the Maine and MFRC models' representation of the forest. An increased understanding of the model will allow the reader to better understand what questions the model can address.

The budworm-forest simulation model is best thought of as a budworm-foliage model. The model carefully keeps track of budworm densities, foliage consumed by budworms, foliage response, and the effect of foliage depletion on budworm survival. The simulation model also includes a prediction of tree mortality, which is less reliable than the other relationships because of the failure of field studies to determine the relationship between defoliation and tree death rates. Tree-growth loss has not been modeled at all.

The two models' representation of budworm population dynamics is based mostly on data collected in the Green River study reported in Morris (1963). Later research at the MFRC has also been incorporated. Budworm survival and success is modeled during each of the six life stages: eggs, first and second instar larvae, third and fourth instar larvae, fifth and sixth instar larvae, pupae and adults. The availability of foliage affects larval survival during the six instar stages. Budworm densities during all stages were expressed as individuals per ten square feet of foliage. Results are given here in individuals per square meter.

The Maine model's forest-dynamics submodel describes the behavior of the budworm's host trees in a 36 square mile site. A fixed portion of this area is assumed always to be covered by spruce-fir. The model describes the trees on a site by their age distribution and the density of foliage on the trees' branches. These variables summarize the important history of the forest and its potential for harvesting and budworm infestation. The MFRC/IRE model is very similar. Because budworms prefer and survive better on the current year's growth, the models differentiate between the current year's growth, referred to as new foliage, and needles produced in previous years, referred to as old foliage.

Model Validation

Stedinger (1977ab, 1984) discuss the differences between the Maine and MFRC/IRE models. The differences relate primarily to the density-dependent larval survival functions employed and the relationships assumed between budworm densities and foliage consumption, and foliage consumption and budworm survival. Also reported is a detailed analysis of the implications of these differences on overall model characteristics.

Model validation is a crucial step in the modeling process. It is important to demonstrate that when the individual parts of a model are joined together, the complete model adequately reproduces the behavior of the real system. The rigor with which a model can be validated is constrained by the quantity and quality of available data. Concurrent measurements of budworm population densities, defoliation rates, relevant weather conditions, moth invasion densities and spraying history would be necessary for a rigorous model validation; such complete histories are not available. The most reliable and easily generalized data available for budworm-forest model validation are histories of the defoliation rate of new foliage in managed budworm outbreaks. Stedinger (1977ab, 1984) discuss historical defoliation patterns and shows that the MFRC/IRE model is inconsistent with field experience whereas the Maine model with the improvements it incorporates performs reasonably.

Simulation Results

In the "managed" budworm-forest simulations reported here, the forest is assumed to be managed to achieve a sustained yield. This means that the tree-age distribution in each site is close to a steady-state distribution. We will investigate the amount of spraying required to protect the forest if different spraying policies are implemented. One simple policy is to spray any site whose egg density the previous summer exceeded 320 eggs per square meter. This policy sprays when budworm densities are relatively low; hence it is a low egg-density-threshold spray policy, referred to as the 320 spray policy.

A second policy, shown in figure 1, is called the "forest-protection policy," abbreviated FP. This policy sprays any site whose egg and foliage density map into the shaded region at the bottom of the figure. These are forest states in which tree mortality might occur if spraying does not protect the foliage. This is an approximation of the forest-protection policy in use in Maine and New Brunswick.

The third spray policy shown in figure 1 sprays any site whose egg and foliage density map require spraying to protect tree health or whose egg density exceeds 650 eggs per square meter. This will be referred to as the 650 spray policy.

In addition to the dispersal of moths by prevailing winds among the 80 modeled sites, the model includes a mechanism, such as the passage of a cold front, which deposits a large number of moths in a limited area. This occurs any year with a 20% probability. When it does occur, it deposits 3.16×10^6 eggs/acre (about 160 eggs per square meter).

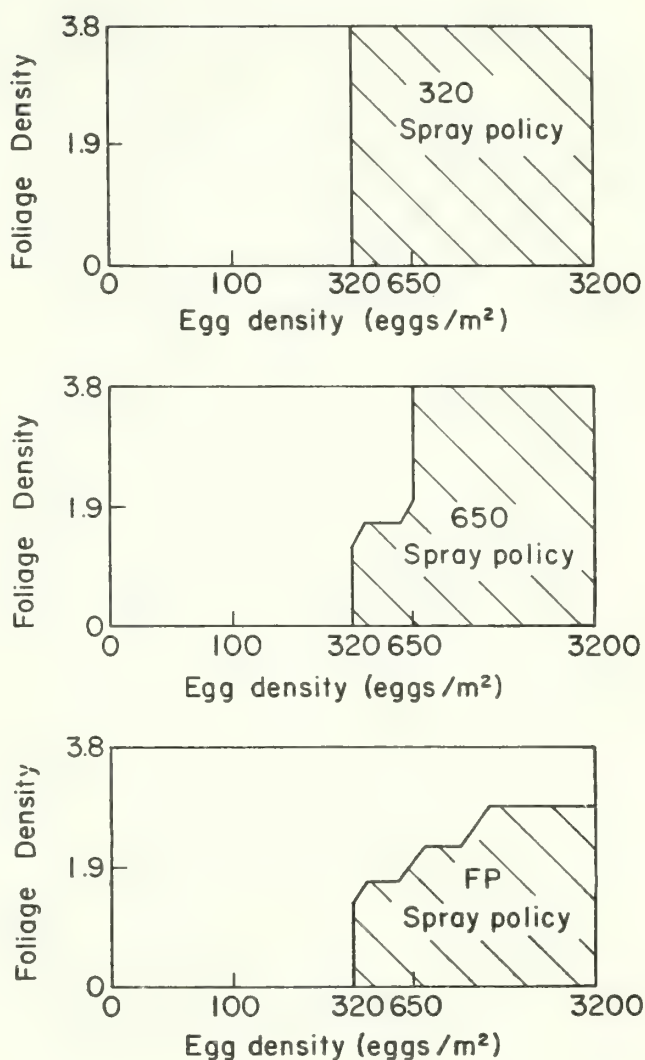


Figure 1. Three spray policies used in forest simulations. With each policy a site is sprayed if its state as determined by the site's egg and foliage densities falls in the shaded regions.

Table 1 reports the simulation results with the three policies. Reported in the table for each policy are the resultant spray frequency or average proportion of the forest sprayed each year, average egg density, and average defoliation rate (as a percentage of new foliage produced each year). The low egg-density-threshold spray policy is clearly superior to the other two policies. Its use results in less than half as much spraying and in almost no defoliation. These results show that the suppression of budworm populations before they reach outbreak densities is superior to spraying only when tree health is threatened. By waiting, one allows infestations to spread to other areas; when an area is sprayed, its budworm population is soon reestablished by moth flights from areas which are not sprayed. Thus by waiting, more spraying is required and one can be fairly confident that epidemic budworm levels will persist indefinitely without the assistance of moth invasions from remote outbreaks. Given that current strategies allow moderate budworm density populations to persist in many places and given that the basic budworm host (i.e., the white/red spruce and fir trees) remain in moderate condition, there seems to be no reason why the current outbreak in New England should collapse. (See also Blais, 1974).

Table 1. Summary of simulated budworm-forest behavior with the 80-site Maine budworm-forest model.

Policy	Spray Frequency (Sites Sprayed/Year/Modeled Site)
320	0.062
650	0.156
FP	0.162

Policy	Average Egg Density (eggs/m ²)
320	87
650	330
FP	427

Policy	Average Defoliation as a Percentage of New Foliage Produced
320	6.5
650	26.4
FP	38.2

Also of interest is the budworm-forest dynamics predicted by the MFRC/IRE model with these policies. The average spraying frequency obtained with the MFRC/IRE are reported in Table 2. With this model, the FP policy does slightly better than the 650 rule because of the very poor condition of the stands and the resultant decrease in budworm survival (see Stedinger, 1977a, pp. 3-35-3-38). With the MFRC/IRE model, the FP policy results in an 18% decrease in the volume of wood harvested due to tree mortality from that harvested with the 320 rule. Tree-growth losses due to defoliation which decrease the sustained yield even farther.

Table 2. Spray frequencies in simulations with MFRC/IRE model and its estimated standard error. a/

Policy	MFRC/IRE Model
320	0.058
650	0.187
FP	0.141

a/ These results were actually computed using a spatially-simplified 10-site model. Compare with second row of Table 3 which also used a 10-site model.

Sensitivity Analysis

An extensive sensitivity analysis with the Maine model was conducted to determine if possible model errors could cause low egg-density-threshold policies to be inferior to forest-protection policies. The superiority of low density-threshold policies is not affected by what are considered to be possible errors (Stedinger, 1977a, pp. 3-46 to 3-60). For these sensitivity runs, a one-dimensional compression of the two-dimensional Maine model was used. Table 2 shows the results of an error of -16% or +20% in the modeled scale of budworm survival. As the values in the table show, such an error has a large effect on spray frequencies, but not on the superiority of low density-threshold policies. However, if budworm survival has been underestimated, then an egg-density threshold lower than 320 eggs would be preferable.

Table 3. Spray frequencies are given for three policies when large larval survival was scaled by indicated factors. b/

Scale Factor	Spray Policy		
	320	650	FP
0.84	0.042	0.084	0.132
1.00	0.078	0.185	0.179
1.20	0.170	0.263	0.215

b/ These results are computed with spatially-simplified 10-site model.

The New Brunswick Task Force Report using the MFRC/IRE model identified 86 eggs per square meter as a good spray threshold. Both the Maine and MFRC/IRE models indicate that low egg-density threshold policies are best though they point to different optimal spraying thresholds. Research on budworm survival in the 10-400 egg per square meter range would allow better identification of an appropriate egg-density threshold for spraying. An operational spraying strategy could have a threshold which is a function of geographical location, stand age, or other important considerations which relate to budworm survival or to the ability of moths to disperse into or out of an area.

Conclusion

The simulation model indicates that if budworm outbreaks are initiated by limited "point sources," such as infrequent moth inflights or small epicenters, then it is advantageous to suppress budworm populations before they build up to outbreak densities. If suppression operations take place only in areas with high budworm densities and severe defoliation, then infestations spread and sprayed areas are soon reinfested by moths from surrounding unsprayed areas. Interestingly, the superiority of early control action has also been observed in other multi-site budworm simulation studies (Watt, 1964; Baskerville, 1976).

Use of a low-egg-density-threshold policy has the advantage that the forest is maintained in a healthy vigorous state without tree growth loss rather than on the brink of collapse as occurs with the forest-protection policy. It also minimizes the potential for widespread tree mortality should weather, technical difficulties, or political events prohibit the

execution of a spray program for one, two or three years. This policy is, in some sense, resilient against unexpected events (Stedinger, 1977a, p. 4-45 to 4-58).

Unfortunately, use of a low egg-density-threshold policy may be politically unstable because it eliminates the immediate danger of widespread tree mortality. This would encourage political institutions and budget-conscious decisionmakers not to vigorously maintain necessary low-budworm-density monitoring networks and early suppression spray programs; the result would probably be an unintentional return to a forest protection policy.

It is interesting that current management strategies are stressing effective forest management and manipulation, and use of dead and dying timber, to decrease forest vulnerability, and to minimize the need for spray operations rather than employing low-density budworm suppression programs. Thus, forest managers have chosen to take advantage of management opportunities which are not well described or available in the Maine and MFRC/IRE budworm-forest models.

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INVENTORY INFORMATION

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Risk-rating procedures should be simple, easily understood, and readily adaptable to local conditions. Both the number of variables and the number of classes within each variable should be kept to five or less. One procedure for short-term risk-rating which can be used with ground or air photo determinations of defoliation and mortality is described.

Introduction

Several procedures have been developed for assessing short-term or long-term risk from spruce budworm activity (Batzler and Hastings 1981; Witter and Lynch 1984). Some rely on ground techniques, some on aerial techniques, and some on a combination of aerial and ground techniques. Variables measured, or considered, in long-term risk-rating often differ from those in short-term risk-rating procedures. Differences in objectives are the basis for many of these differences.

The most useful risk-rating procedures are those which are simple, easily understood, and readily adaptable to local conditions. Such procedures seldom evolve unless there is agreement on what is to be accomplished and the meaning of terminology. Let's be sure you understand what I mean by two key words in the title of this paper.

Risk can have many connotations. It can have a meaning which is value-oriented, as in values at risk and risk of loss; occurrence-oriented, as in risk of attack; or control-oriented, as in risk of spread (of a damage agent). The first of these, with a value orientation, usually includes elements of each of the other two. Because there is little need to take corrective or preventive action if there is no value at risk, I associate risk-rating with value.

Inventory can be considered the determination of value at some point in some utilization cycle (Olson 1983). Because value can seldom be measured directly, we usually concentrate on those things we know how to measure which are correlated with, and let us predict, value. Foresters traditionally measure tree diameter and height to determine the value of the wood in a tree. This may not be the most appropriate way to determine the value of a shade tree, or a stand of trees as wildlife habitat. In deciding what to measure, we should select whatever provides the most cost-effective basis for determining the desired value(s), at the appropriate point(s), in the intended utilization cycle(s).

Selecting What And When To Measure

Selecting the right variables to measure for risk-rating requires an understanding of both the biology and ecology of the damage agent. When the damage agent is the spruce budworm, Choristoneura fumiferana (Clem.), there are a number of factors to consider (Witter et al. 1984). Some of these are:

1. Active feeding is usually confined to the months of May, June, and July.
2. Attack is seldom fatal in the first season.
3. Mortality is greater when:
 - a. over half of the stand is of host species, balsam-fir (Abies balsamea (L.) Mill.) or spruce (Picea spp.).
 - b. the stand is very open or dense.
 - c. large amounts of foliage of host species are exposed (trees not overtopped).
 - d. average age of host species is more than 50 years.
 - e. the site is very wet or very dry.

Some of these factors are closely related to each other (e.g., stands over 50 years of age usually have large amounts of foliage of host species exposed). The degree of correlation often varies between regions and within regions (Blais 1968; MacLean 1980; Lynch et al. 1984).

Selecting the right variables to measure for risk-rating requires an understanding of possible utilization cycles. If rotation age is kept below 50 years (Flexner et al. 1983), individual trees will seldom reach sawtimber size. Deterioration caused by secondary insects and fungi soon renders pole-sized trees susceptible to breakage. Salvage is seldom practical more than two years after death of balsam-fir, or three years after death of spruce. The number or proportion of dead trees already present in a stand is a factor affecting probable loss if prompt action is not taken.

Selecting what and when to measure also requires common sense. Because active feeding usually begins in May and extends into July, ratings made during these three months are single point assessments of moving targets. Salvage or preemptive cutting can seldom be accomplished before the next cutting season, and it is appropriate to delay risk-rating for spruce budworm until the active feeding period is over. In Michigan's Upper Peninsula, August and September usually provide the best flying weather. Photographs taken, or field work, in August and September provide ratings for consideration in October and November when cutting plans are made for the following harvest season. Delaying risk-rating until August or September presents one problem. Brown needle mats which are one visible indicator of feeding activity are often gone - removed by wind and rain. This is not, however, a serious problem.

Long-Term and Short-Term Risk-Ratings

Long-term risk-rating procedures are designed to assist forest managers in planning stand management and harvest operations over long periods. They are usually based on conventional inventory data. Such data usually include, for each stand:

1. Number of live and dead trees, by species.
2. Basal area, by species, from which stand density determinations can be made.
3. Stand age.
4. Site quality, including information on relative wetness or dryness.

These are the data needed to assess four of the five mortality factors identified on the previous page. Several regression equations have been developed to predict potential for loss from such data (Witter and Lynch 1984). Such equations are readily implemented within computer-based forest information systems. They are not as readily implemented in the field, and seldom meet the need for short-term risk-rating under outbreak conditions.

Most short-term risk-rating procedures are designed to assist forest managers minimize loss once an outbreak has begun. They are designed to identify those stands with the highest probability of loss in the short-term, and require current information for each stand. Such data are seldom available from normal inventories based on re-measurements at five-year, or longer, intervals. Short-term risk-rating procedures should be considered supplements to normal inventory procedures. As such, their function should be to provide information on the more dynamic and changing variables. Has the stand been attacked yet? If so, how severe is the attack now? How quickly must the stand be salvaged to avoid unacceptable loss?

Managing Costs

The most visible signs of spruce budworm attack are defoliation and mortality. Ground procedures for assessing present damage and predicting future loss of individual trees have been developed based on these two variables (Mog and Witter 1979). Combining data for individual trees provides a risk-rating for a stand. This is a short-term risk-rating, and requires current, usually annual, data. McCarthy et al. (1982; 1983) reported that equivalent measurements could be made from large-scale, small-format, color, air photos without the need to send ground crews into each stand. Use of such methods may not reduce costs, but should provide more information at acceptable cost, when compared with costs of obtaining the same information from ground methods alone.

Because it is seldom feasible to measure all of the trees in a forest population, foresters commonly base decisions on measurements of a sampled sub-set of the total population. Cost of field measurements usually restricts the number of

samples that can be measured. Air photo technique can provide a larger sample size for a given cost and are adaptable to either random or systematic sampling designs. For air photos to be useful, available personnel must be able to make the needed interpretations. Experience has shown that the needed skills can be provided with two to three days of training.

Designing A Short-Term Risk Rating Procedure

Experience indicates that procedures utilizing both ground and aerial techniques are more effective than those using either technique alone. To provide readily comparable data, both ground and aerial techniques should utilize the same rating procedure. This results in a total procedure which is simpler and easier to understand than when different variables are measured on the ground and from the photos. Such a common procedure has been designed for short-term risk-rating in Michigan's Upper Peninsula (Olson et al. 1982).

Basic Considerations

A low cost, simple procedure for risk-rating should rely on as few variables as possible. Variables selected should be easily measured by the personnel expected to make the measurements. After reviewing several types of rating procedures, we concluded that neither the number of variables nor the number of classes within a variable should exceed five, and preferably be limited to four. Humans are three-channel processors whose efficiency declines when confronted with decision processes requiring integration of more than three inputs. Four or five variables can fit into a 3-channel system if variables are appropriately combined. More than five subdivisions within a variable provides more detailed ratings than the precision of our current knowledge justifies.

Because forest terrains are seldom flat, forest areas have few dependable landmarks, and light aircraft used in taking small-format air photos seldom have precision altimeters, it is seldom possible to accurately determine the scale of 35mm air photos of forest areas. When photo scale is not accurately known, the ground size of sample plots located on those photos cannot be determined. To overcome this problem and still provide the cost advantage of sampling procedures and 35 mm photographs, we decided to base our rating procedure for spruce-fir stands on stand averages and proportions. The resulting procedure is not dependent on constant plot size or a given sample size, and may be used on the ground, with air photos, or with a combination of ground and photo measurements.

Variables Selected for Measurement

The procedure designed for Michigan's Upper Peninsula is based on measurement or estimation of four variables:

1. Relative density of the stand, based on the rater's estimation that the stand is open,

average, or dense.

Proportion of stand in host species, determined by dividing the total number of host trees by the total number of trees of all species.

Average defoliation ranking of live trees of host species, based on the following scale:

1 = No to 20 percent defoliation.

2 = 21 to 50 percent defoliation.

3 = 51 percent or more defoliation, without top kill.

4 = 51 percent or more defoliation, with one meter or more of top kill.

Proportion of host trees already dead, determined by dividing the number of dead host trees by the total number of live and dead host trees.

Values of each of the last three variables can be calculated for each host species separately, if desired. Some modification of the rating tables would be required if this is done.

Rating Tables

Three tables were developed for determining the contributions of the four selected variables to a final Stand Rating Index (SRI). Individual values in each table represent best estimates of the appropriate weight to be assigned to that cell in the table. Among the factors considered when making these assignments were:

Value of host species at risk. When large numbers of trees of host species are present, the potential for loss is greater than when fewer trees of host species are present. Thus, dense stands have more value at risk than open stands, and stands with a high proportion of trees of host species have more value at risk than stands with a low proportion of trees of host species.

Number of years the stand has been attacked. Duration of attack was assumed to be correlated with average defoliation ranking for the stand. High defoliation rankings indicate multiple year attacks with a higher probability of future short-term mortality.

Present mortality. The presence of significant numbers of dead host trees usually indicates multiple year attacks. Additional mortality in the short term is likely. Because dead trees deteriorate quickly, prompt salvage is necessary to reduce loss. When mortality is very high, however, deterioration may be sufficiently advanced to make salvage unlikely.

All of the values in the tables are subject to modification and adaptation to local conditions without altering the basic procedure. This has made the procedure adaptable to requirements of different organizations, or local utilization and salvage practices.

Table 1. Contribution to Stand Rating Index (SRI) based on stand density and proportion of stand in host species.

Proportion of Stand in Host Species	Stand Density		
	Open	Average	Dense
0.00 - 0.30	1	1	2
0.31 - 0.60	2	3	4
0.61 - 1.00	3	4	6

Table 2. Contribution to Stand Rating Index (SRI) of average tree defoliation ranking.

Average Defoliation Ranking	Contribution to Stand Rating Index
0.0 - 1.2	0
1.3 - 1.9	1
2.0 - 2.9	2
3.0 - 4.0	3

Table 3. Contribution to Stand Rating Index (SRI) based on present mortality of host trees.

Proportion of Host Trees Already Dead	Contribution to Stand Rating Index
0.00 - 0.09	0
0.10 - 0.29	2
0.30 - 0.49	4
0.50 - 1.00	6

Procedure

The procedure presented here is based on the use of 35mm, color, air photos at a scale close to 1:4,800. Interpretation of the original, positive transparencies was completed stereoscopically with adjacent, overlapping photos. For a more complete description of the procedure, and its development, see Olson et al. (1982).

Modification of this procedure for ground use is straightforward. Plot size is often larger in ground surveys, for non-productive travel-time between plots can be a significant cost factor. With the photos, we found a plot which included between 12 and 20 trees was a good size. Larger plots included so many trees that interpreters sometimes lost track of which trees had been tallied. Others things being equal, many small plots usually provide as good, or better, results as fewer larger plots.

The procedure presented here will not provide a quantitative prediction of future loss. Instead,

it provides a numerical index, or Stand Rating Index, that can be used to compare spruce-fir stands and rank them in terms of probability of short-term loss.

Step 1. Select the size of sample plot to be used.

Step 2. Determine locations of sample plots on the photos. These locations may be randomly or systematically selected.

Step 3. Place a template defining plot size over each plot location. A small piece of clear acetate with a marked plot outline works well.

Step 4. Tally all trees within each plot by species, and record a Defoliation Ranking for all living trees of host species. Keep a separate tally of the number of dead trees by species.

Step 5. Compute the proportion of the stand in host species by dividing the number of host trees in the total tally (all plots in a stand) by the total number of trees tallied for the stand.

Step 6. Compute the Average Defoliation Ranking for the stand by summing the defoliation rankings for each living host tree and dividing by the number of living host trees.

Step 7. Compute mortality of host trees by dividing the number of dead host trees by the total number of living and dead host trees.

Step 8. Estimate the density of the stand as Open, Average, or Dense.

Step 9. Look up the contributions to the final Stand Rating Index from each of the tables and sum these individual contributions to obtain the final SRI.

Interpreting the Results

If we use the procedure presented above and determine ratings for six stands, we might get the following results. How can these results be interpreted?

Contribution from Table #	Stand					
	1	2	3	4	5	6
1	2	4	6	2	4	3
2	2	3	2	3	1	3
3	0	4	2	2	0	4
SRI (sum)	4	11	10	7	5	10

Stand 2 has the highest SRI. It is a dense stand with about half of the trees of host species, live host trees are heavily defoliated, and one-third to one-half of the host trees are already dead. If this stand is not cut soon, there will be little left to salvage.

Stands 3 and 6 both have ratings of 10. On the basis of present damage, defoliation plus mortality, Stand 6 is in worse shape than Stand 3. You might decide to cut Stand 6 first, and delay

cutting Stand 3. Or, you might decide the high mortality in Stand 6 will make logging difficult. A decision to cut Stand 3 preemptively may be more in keeping with local realities.

Stand 1 has a lower SRI than Stand 5 (4 vs. 5). Neither stand has significant mortality, but higher defoliation in Stand 1 may prompt its earlier cutting.

Stand 4 has a high defoliation rating and significant present mortality. Its SRI is lower than that of Stand 3 only because it contains less spruce and fir. It has less value at risk. Some users of this procedure have elected to increase the values in Table 2, to give greater weight to levels of present defoliation. If all values in Table 2 are doubled, the results would be:

Contribution from Table #	Stand					
	1	2	3	4	5	6
1	2	4	6	2	4	3
2	4	6	4	6	2	6
3	0	4	2	2	0	4
SRI (sum)	6	14	12	10	6	13

The primary effect of this change is to more clearly group the six stands into two groups, those with values of 10 or more, and those with values below 10.

Final Remarks

As this meeting has shown, great progress has been made in building the knowledge base from which to more accurately forecast both long-term and short-term losses due to spruce budworms. Implementation of this knowledge should result in better management decisions. This will only happen if the information can be effectively condensed into some acceptable index, for experience has repeatedly shown that managers presented with too much information tend to ignore all of it. Regression equations based on twenty, or even ten, variables are seldom acceptable to forest managers, although this appears to be changing as more and more managers become accustomed to computer-based forest information systems. Still, risk-rating procedures which are not simple, easily understood, and readily adaptable to local conditions will probably see little use.

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STAND MANIPULATION TO TAKE ADVANTAGE OF NATURAL MORTALITY FACTORS

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The value of stand manipulation for increasing levels of mortality of early larvae of the spruce budworm was assessed. The geographic regions and situations in which manipulation techniques would likely be effective are identified and recommendations are made for managing stands to increase early larval mortality.

The term "larval dispersal loss" has usually referred to mortality occurring to spruce budworm larva during two periods--immediately after egg hatch in August or September and again after emergence from overwintering hibernaculae in April or May (Miller 1958). During these times the tiny larvae often spin and dangle on silk threads and are then launched by puffs of wind (Kemp and Simmons 1979). The difficulty of studying these phases of the budworm life cycle led Miller to refer to mortality as "larval dispersal loss" even though the total mortality could be ascribed to a variety of causes including predators, maladaptation, weather and other factors, in addition to larvae landing on unsuitable host material. When we refer to "larval dispersal losses" we take the broad, all encompassing interpretation by Miller and expand somewhat to include "all mortality occurring, beginning with egg disposition until 3rd and 4th instars are established in feeding sites in the spring"

This phase of spruce budworm population dynamics has been studied by different investigators in several locations throughout eastern North America, and with related budworm species in other parts of the continent (Henson 1950, Miller 1958, Morris and Mitt 1963, Foltz et al. 1972, Shaw and Little 1973, Kemp and Simmons 1979, Batzer and Jennings 1980, Kemp et al. 1980, Beckwith and Burnell 1982, Nyrop et al. 1982, Régnière and Fletcher 1983, and Jennings et al. 1983). Whether one studies the literature, conducts system simulation studies or investigates field dynamics, the overwhelming conclusion is that mortality during this period is consistently high. For example, Miller (1975) gives values of 60-80%, Kemp and Simmons (1979) from 76-99% and Nyrop et al. (1982) around 86-87%.

Over the past 10 years my students and I have investigated various aspects of the budworm's biology, forest character and cultural treatments of the forest to see if the forest could be manipulated to take advantage of the multitude of mortality factors that affect the budworm during the early part of its life cycle. We have developed both field studies (Kemp and Simmons 1978, 1979, and Nyrop et al. 1982) and computer simulation studies (Kemp et al. 1980, Nyrop

et al. 1982). Based on these studies and those contributed and reviewed by later speakers, I believe we can make specific recommendations to you.

The recommendations we make are appropriate to geographic regions on the southern edge of spruce-fir type such as portions of Minnesota, Wisconsin, Michigan, New York, Vermont and New Hampshire. Techniques are also appropriate on small parcels of land where intensive, multiple use practices are currently employed or are desired. The last qualifiers are that a substantial portion of the land area (30-50%) is not needed for producing trees and that treated stands should contain mixtures of budworm non-hosts such as aspen, birch, red maple or northern hardwood species.

General Guidelines

1. Keep spruce and fir under 50 years of age.

This assures young, vigorous trees that are able to sustain an outbreak without undue tree mortality.

2. When stands are less than 20 years old, create strips of open area between stands of trees.

Strips should cover 30 to 50% of the total land area. Each open strip should not be less than 3 chains in width and each forested strip should not exceed 5 chains in width. Open strips can be created by cutting, bulldozing, rollerchopping, burning, herbiciding or combinations of methods. The open strips and forested strips should take maximum advantage of budworm mortality factors such as dispersal, parasites and insect and bird predators. The reason for early treatment of stands is to start grooming stands early for windfirmness.

3. Open strips need to be maintained at approximately 10-15 year intervals.

The advantages of open areas are lost with time due to forest succession. Thus, the open strips will require attention occasionally. The same methods mentioned in 2 can be used to recreate open areas.

4. Discriminate against balsam fir in the forested strips.

The higher the percentage of fir and the older it is, the more likely it is to suffer damage during a budworm outbreak. Ideally, the combination of spruce and fir should not exceed 60% of the basal area of the forested strips.

5. Discriminate against individual spruce or fir trees that dominate the height of the forested strips.

Individual spruce and fir trees that stand above the canopy are attractive to ovipositing spruce budworm moths. By selecting against these kinds of trees you are making the stand less desirable from the budworm's point of view.

The utility of the above techniques is obviously limited to circumstances where spruce and fir stands are small, isolated and contain mixtures of other tree species. In addition, the methods discussed are most appropriate where intensive, multiple use is the objective of management. Small, private woodlots and isolated stands along the southern distribution of spruce-fir type are, to us the places where these methods show promise.

In areas where spruce-fir is common, widespread and extensively managed with large scale aerial spraying operations, these methods are both inappropriate and likely to be uneconomical. Some of our research experience was obtained in these kinds of settings and the results were not satisfactory. Further, we feel these techniques will not work well in mature stands--if stands are beyond 30 years of age we believe these techniques may create more problems than they alleviate.

Thus, the approach we suggest is one additional set of tools to choose from that can match particular circumstances. These techniques do not provide a cure-all to be applied over large geographic areas.

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EFFECTS OF SILVICULTURAL PRACTICE ON BIRD PREDATION

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Several species of birds were effective predators on endemic spruce budworm populations. Populations of these birds can be improved by silvicultural practices that increase: (1) the degree of hardwood admixture with softwoods, (2) the proportion of spruce to fir, and (3) the diversity in horizontal and vertical habitat structure. Group selection and shelterwood cuts were favored.

Recent evidence indicates that birds may limit increases of endemic spruce budworm (*Choristoneura fumiferana*) populations. Crawford et al. (1983) estimated that birds ate approximately 87% of SBW pupae and larvae in endemic situations and concluded that "birds have the ability to consume substantial numbers of late-stage larvae and pupae of the spruce budworm and hypothesize that under favorable conditions birds may prevent budworm populations from becoming epidemic." What are the favorable conditions that would enhance control of SBW by birds?

Important Predators Of Spruce Budworm

Bird predation has little effect on epidemic spruce budworm populations, though many species eat the pupae and larvae (Crawford et al. 1983). Insects are so numerous that the number eaten by birds is small in relation to the total available. When the budworm is not at epidemic levels, fewer bird species eat the insect but the proportion of the population eaten is greater. Predators that maintain high population densities and high feeding rates over the lower ranges of the insect's density and that respond to initial rises in endemic numbers are most important in insect suppression. In northern New England, species that met these criteria were the blackburnian warbler (*Dendroica fusca*), golden-crowned kinglet (*Regulus satrapa*),

Nashville warbler (*Vermivora ruficapilla*), white-throated sparrow (*Zonotrichia albicollis*), black-capped chickadee (*Parus atricapillus*), solitary vireo (*Vireo solitarius*), red-breasted nuthatch (*Sitta canadensis*), magnolia warbler (*D. magnolia*), and yellow-rumped warbler (*D. coronata*), (Crawford et al. 1983).

Response Of Birds To Forest Change

Several studies have shown that changes in forest habitat cause changes in the number and species composition of birds. Clearcut harvest of Douglas-fir (*Pseudotsuga menziesii*) caused marked changes in bird species composition in California (Hagar 1960). Species of birds using different stages of forest succession following timber harvest in coniferous forests of Finland changed as habitat structure of the forest stands changed (Haapanen 1965). In northern Maine spruce-fir (*Picea-Abies*) stands, the distribution of breeding songbirds was determined by habitat structure in each of 5 seral stages following clearcutting (Titterington et al. 1979). Crawford and Jennings (1982) hypothesized that natural predation on forest insects can be enhanced by habitat manipulation, which increases numbers and variety of birds.

Three intrinsic habitat factors determine woodland bird populations in the northern spruce-fir stands we have studied: (1) the degree of hardwood admixture with softwoods, (2) vertical and horizontal stand structure, and (3) the degree of spruce budworm infestation (Crawford and Titterington 1979). Bird populations also can fluctuate because of factors such as winter mortality, migration loss, etc. The intrinsic factors vary from stand to stand. Hardwood-softwood mixture and stand structure depend on geographic location, microclimate, site characteristics, past cutting, and within-stand silviculture. Spruce budworm populations appear cyclic and are affected by weather and the amount, age, and distribution of balsam fir in the stand.

Crawford and Titterington (1979) found that stands composed primarily of balsam fir contained an impoverished avifauna with an average of only 128 breeding pairs/40 ha and 20 bird species (Table 1). Stands of mixed spruce and fir averaged 190 pairs/40 ha with 26 species. An admixture of hardwoods and conifer in the overstory increased the bird

population to 231 pairs/40 ha with 24 species. Reproducing spruce stands with saplings and poles and mature spruce stands supported 249 and 264 breeding pairs/40 ha with 17 and 23 species, respectively.

Table 1. -- Bird Density and Composition by Forest Type

Forest type	40 ha Pair	No. of species	Multiple
Balsam fir	128	20	1.0
Spruce fir	190	26	1.5
Mixed growth	231	24	1.8
Young spruce	249	17	2.0
Mature spruce	264	23	2.1

Bird populations in seral spruce-fir stands followed a predictable pattern in northern Maine (Titterton et al. 1979). The earliest seral stage was characterized by dense slash and open ground that dominated the site for 2 years following commercial clearcutting. The dark-eyed junco (*Junco hyemalis*), white-throated sparrow, and winter wren (*Troglodytes troglodytes*) commonly occupied these areas. A dense raspberry stratum generally occupied the site 3 to 5 years after cutting and favored populations of the common yellow-throat (*Geothlypis trichas*), mourning warbler (*Oporornis philadelphia*), chestnut-sided warbler (*Dendroica pensylvanica*), and white-throated sparrow. Hardwood regeneration taller than 2 m and a slow-growing softwood stratum characterized the next seral stage that lasted from 7 to 12 years after cutting. Dominant bird species in this stage were the magnolia warbler, American redstart (*Setophaga ruticilla*), red-eyed vireo (*Vireo olivaceus*), black and white warbler (*Mniotilta varia*) and white-throated sparrow. The fourth seral stage is characterized by increased densities of hardwood regeneration taller than 4.5 m with a dbh of 10-15 cm and scattered hardwood residuals. Attendant birds included the ovenbird (*Seiurus aurocapillus*), black-throated blue warbler (*D. caerulescens*), black-throated green warbler (*D. virens*), Canada warbler (*Wilsonia canadensis*), Swainson's thrush (*Catharus ustulatus*), rose-breasted grosbeak (*Pheucticus ludovicianus*), and Tennessee warbler (*Vermivora peregrina*).

Mature spruce-fir stands with a dense softwood overstory and an open forest floor represented the fifth seral stage. The Blackburnian warbler, golden-crowned kinglet, bay-breasted warbler (*D. castanea*), yellow-rumped warbler, and Cape May warbler (*D. tigrina*) dominated the avifauna.

Enhancing Predators Through Silvicultural Practices

Spruce and fir along the northern border of their transcontinental distribution often are found in almost pure stands. Intolerant hardwoods such as the birches (*Betula* spp.) and aspens (*Populus* spp.) increase toward the central latitudinal portion of this distributional belt. Along the southern border, mid-tolerant and tolerant hardwoods such as beech (*Fagus grandifolia*) and maples (*Acer* spp.) compete with spruce and fir for favorable sites.

Although hardwoods are naturally more abundant in the southern portion of the upland spruce-fir type, site characteristics substantially influence their distribution and abundance. Spruce and fir on thin, infertile soils in the moist eastern portion of the range generally grow in dense stands with closed canopies and little hardwood admixture. In an undisturbed state these stands are single-storied with sparse undergrowth. More fertile soils allow more hardwood growth and increased canopy layering. In the more continental climate to the west, hardwoods are better competitors for limited soil moisture, and moisture stress increases the mixture of hardwoods in spruce-fir stand (Westveld 1953).

Thus, fir stands in those parts of northern New England and the Maritimes with shallow, infertile soils have dense, shallow canopies with little admixture of hardwoods and sparse understory growth. Such stands represent some of the poorest bird habitat in eastern North America. Silvicultural practices that create greater plant diversity will enhance bird habitat.

Silviculture, when left to the spruce budworm, will favor the spruce budworm. Poor-site, dense fir stands often are underlain by deep organic mats. The long hypocotyl of fir seedlings penetrates the deep organic mat to reach mineral soil. Primary roots of other competitors are not as effective and may desiccate during dry

periods. Thus, when the overstory is defoliated by spruce budworm, small fir regeneration is released and soon fully occupies the site, producing another dense fir stand which provides food for the budworm and unfavorable habitat for birds.

Large clearcuts simulate the silviculture practiced by spruce budworm. Dense stands of fir result from copious preharvest regeneration unless the site is altered by burning or is intensively prepared, planted, and cultured after harvesting. These practices are not used extensively by forest managers. Thus, the usual large clearcut on poor sites produces another fir stand favorable for budworm and unfavorable for birds. Hardwoods occur naturally with fir on better sites but often are discriminated against in management programs. Regenerating stands that contain a large proportion of spruce will provide substantially better bird habitat than fir stands because they support high populations of magnolia warblers and other effective budworm predators.

Four effective budworm predators--blackburnian warbler, golden-crowned kinglet, yellow-rumped warbler, and red-breasted nuthatch--are associated with mature conifers, especially a mixture of conifer species. Other effective budworm predators--Nashville warbler, white-throated sparrow, and black-capped chickadee--are associated with brushy openings and the edge between openings and spruce-fir or mixed growth. The magnolia warbler and solitary vireo, also effective predators, favor immature, open conifer stands and dense stands of hardwood stems, conditions typical of regenerating forests. Thus, a mature coniferous forest with a mixture of overstory species, managed for well-distributed, small openings containing regeneration of different ages, should provide habitat to favor the best population of budworm predators. We do not have data to confirm the most effective size of opening but small patches would be necessary because territory size of most of these predators generally is less than 1/2 ha.

Of the alternatives for silvicultural practice, group selection comes closest to creating these ideal conditions. Considering only even-age alternatives, three-stage shelterwood could provide suitable habitat if the operating units are small, perhaps 10 ha and of different ages.

We find one alternative for uneven-age and one for even-age management to produce the best populations of predaceous birds. Either alternative involves a change in the scale of harvest activities that we practice today. Either system would require more maneuverable harvesting equipment. Changes in costs of harvesting will have to be compared to change in costs of insect control. If more effective insect control at lessened costs offsets increased harvesting costs, then bird management, in concert with other insect control measures, could present a viable management strategy.

We are now conducting research to quantify the effects of bird predation and evaluate its contribution to integrated pest management.

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EFFECTS OF STAND CONDITIONS ON PARASITOID DYNAMICS

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The success of parasitoids in spruce budworm suppression rests on their ability to find and parasitize hosts in numbers proportional to host levels. Different ways of managing forest stands to decrease their vulnerability to spruce budworm are discussed in light of their inevitable influences on parasitoid ecology.

The goal of the silvicultural management of the spruce budworm is to create stand conditions which make life difficult for this forest defoliator while maximizing other objectives, e.g., economic and recreational. Effective management includes the regulation of all ecological factors impinging on the spruce budworm's welfare, except perhaps climate and weather. From disease, predation, and parasitism to soil chemistry, these influences interact in an ever-changing network, probably always somewhat out of balance. This paper focuses on one connection in this network: the dependence of parasitoid activity on conditions within forest stands.

Searching Capacity

The ability to find and parasitize hosts, especially at low host density, has significant bearing on the long-term success of parasitoids (Graham and Knight 1965; Debach 1974; Coppel and Mertins 1977). Some of the factors contributing to searching efficiency are systematic searching, avoidance of presearched areas, discrimination against hosts already attacked, and emigration (DeBach and Smith 1941; Burnett 1951; Wylie 1970; Price 1972).

When female parasitoids emerge in preparation for egg laying, they must locate their hosts. Random searching or the chance location of a host are assumed in many parasitoid-host models and may suffice for some species, but such activities do not appear to be advantageous where host densities are low (Vinson 1975).

Forest trees of different sizes and species provide a number of microhabitats for host insects. Effective parasitoids are able to recognize the few microhabitats frequented by their preferred hosts out of the wide range of conditions which any forest has to offer.

A hypothetical parasitoid, starting from scratch, might begin with broad categories of host habitat preference to reduce its search time. The parasitoid pursues the search by making finer and finer discriminations, with the object of maximizing its search time in the microhabitat in which the host is most likely to occur. Chemical cues originating from the host, its food source, or the feeding process can aid parasitoids in their searching behavior. Thus the search can result in biochemical coevolution between parasitoids and their hosts (Vinson 1975). For example, the leaf damage caused by feeding of the tobacco budworm Heliothus virescens (F.) results in increased frequency of landing and increased length of time spent on the plant by the parasitoid Cardiochiles nigriceps Viereck while mechanical damage does not (Vinson 1975).

Parasitoids may attack hosts more readily on some host plants than on others. Miller (1959) showed that female Apanteles fumiferanae Viereck prefer the odor of white spruce Picea glauca (Moench) over balsam fir Abies balsamea (L.) Mill. Parasitoids may reduce or limit their search area to microhabitats associated with their host food plant (Weseloh 1976). Trees differ in the strength of their stimulus to the olfactory responses of the spruce budworm as well, and this can cause host clumping (Morris and Mott 1963).

Theoretically, parasitoids may respond to host pheromones, but we have few reports of such cases (Weseloh 1976). Vinson (1975) suggests that "the utilization of a volatile compound liberated by a potential host as a cue to host location by a parasitoid may be expected in situations where the stage releasing the compound either is attacked or is present along with the potential host stage." The egg parasitoid Trichogramma minutum (Riley) of the spruce budworm or the first and second instar parasitoids A. fumiferanae and Glypta fumiferanae (Vier.) may find the female sex pheromone of the budworm useful in host location because eggs are laid soon after mating, and they hatch in about a week. Since the spruce budworm overwinters as a second instar larva, parasitoids which attack later instars have to depend on other cues for host location.

Forest parasitoids find hosts from a distance by responding to sound, temperature differences, movement, and colors associated with hosts (Weseloh 1976). After a potential host is located, female parasitoids may or may not accept it. Host acceptance and stimulation of egg release depends on host characteristics such as size, shape, surface texture, or motion (Doutt 1959). Arthur et al. (1969) found that a factor in the hemolymph of the host stimulated Itopectis conquisitor (Say) to lay eggs, and that egg laying could be elicited by serine, arginine, leucine, and $MgCl_2$ (Arthur et al. 1972).

There is growing evidence that many parasitoids are able to avoid presearched areas. For example, in a confined area, Griffiths and Holling (1969) found density-dependent interference in oviposition. This suggests that, if unconfined, parasitoids would space themselves so that interference would be reduced. Price (1970) showed that some parasitoid species will avoid areas already searched by others, and that even within a species a female can recognize areas that she and others have searched. At least two common parasitoids of the spruce budworm, A. fumiferanae and Apechthis ontario (Cress.), discriminate between parasitized and non-parasitized hosts (Miller 1959; Ryan 1971). This behavior may result from the recognition of repellent trail odors left by searching females. Price (1972) noted further that in an effort to reduce their exposure to presearched areas, the females will try to disperse. This strategy avoids wasting eggs by discriminating against hosts already attacked by a parasitoid (Ulyett 1950; Burnett 1951; Wylie 1970; May 1978).

Rarely has the occurrence of two or more parasitoids of a solitary species developing in a single host been reported (Brown 1946a; 1946b). By dissecting spruce budworm larvae, McLeod (1977) found that multiple parasitism by A. fumiferanae and G. fumiferanae occurred less than one-third as often as expected by statistical chance.

Lewis (1960) and McLeod (1977) have studied the ovipositional behavior and interaction of A. fumiferanae and G. fumiferanae. A. fumiferanae more readily attacks freely-moving larvae, while G. fumiferanae prefers immobilized immatures in hibernacula. The ovipositor of G. fumiferanae is longer than that of A. fumiferanae and it is easier for the former to pierce hibernacula webbing and deposit eggs in the immature located inside.

The ability of a female to leave viable progeny depends on the compromise between remaining in a host population where exploitation by parasitoids is reaching saturation, and emigration into areas of unknown host resources. This emigration stage would be reached before the host resource is fully utilized because unparasitized hosts become harder to find, and the chances of progeny being hyperparasitized are greater. This demonstrates that density-dependent emigration caused by mutual interaction can be adaptive. Hosts can reach high population densities while interaction between parasitoid females is likely to become severe before this high density is reached (Price 1971). Therefore the capacity of the habitat to support a parasitoid complex may be dictated by the level of interaction between individual parasitoids rather than host supply. The result would be the inability of parasitoid

populations to exploit fully hosts at high population levels. This could account for the decreased efficiency of A. fumiferanae at high host population densities.

Physical factors like humidity, temperature, and light may be partially responsible for the spatial distribution of parasitoids in the forest. For instance, reduced light intensities in cages have been shown to inhibit activity of A. ontario (Ryan and Medley 1972). Flight activity of G. fumiferanae is greatly reduced by rain (Miller 1960; Nyrop and Simmons 1982). Chalcids have one level of activity throughout the day, but braconids increase their activity during the day and ichneumonids are more active in the early morning and evening hours (Juillet 1970). The incidence of A. fumiferanae differs according to tree-crown depth, while parasitization by G. fumiferanae is randomly distributed in budworm larvae at all crown heights (Jaynes 1954; Miller 1958; Dodge 1961).

The effects of host density on parasitism are reflected in the differences in the abundance and diversity of parasitoids attacking epidemic and endemic populations of the spruce budworm (Miller and Renault 1976). Different species of parasitoids respond to changing host densities in different ways. McGugan and Blais (1959) have noted that the parasitoid complex associated with epidemic populations in one area is apt to resemble that in another area. When budworm populations are low, however, the species complex is less predictable (Hanson 1982). Some data suggest that parasitism may be relatively high during the endemic phase, although the species complex is considerably different from that found during an outbreak (Miller 1963; Fye 1963; Miller and Renault 1976).

Those parasitoids of the spruce budworm which have been studied most closely have subtle and complex behavioral characteristics which help explain their presence and abundance (McGugan 1955; McLeod 1977). Nyrop and Simmons (1982) observed that "each parasitoid must be considered individually, even those which attack the same host".

Silvicultural Practices Fostering Parasitoid Success

Should silvicultural planning for regulation of natural enemies take for granted the apparent cycle of epidemics, or rather cater to the possibility that an endemic spruce budworm population will be present during the majority of the stand life? Since the probability of a severe spruce budworm infestation occurring once in the rotation of spruce-fir forest is high (Blum 1984), forest management may be an economically viable means of reducing future budworm impact, though it

may never be a means of controlling budworm outbreaks (Flexner et al. 1983). Budworm and parasitoid populations respond to biological and meteorological factors that are often independent of stand condition.

Recently, Flexner et al. (1983) recommended the following for decreasing the vulnerability of forest stands to spruce budworm:

- (1) Shorten the rotation age of fir to 50 years or less.
- (2) Break up the continuity of extensive areas of mature forests.
- (3) Remove fir from the stand.
- (4) Maintain a mixed-species composition whenever feasible.
- (5) Convert the stand to less susceptible species.
- (6) On a regional basis, optimize the spatial diversity of different even-aged stands.

Most of the silvicultural procedures recommended to reduce the risk of budworm damage are appropriate to an intensive silvicultural program for optimum growth and yield (Blum 1984). How compatible are these recommendations with the creation of favorable habitats for natural enemies? What are the possible influences of changes in the forest environment on the parasitoids' searching behavior?

Few researchers have endeavored to quantify relationships of environmental variables influencing net parasitism (Simmons et al. 1975). Therefore, the effects of stand conditions on parasitoid dynamics that I will be discussing should be seen as possibilities only. Quantitative reports of these effects will only be possible when the results of silvicultural practices now being tried are available.

Shorten Rotation Age of Fir

Stand maturity is considered a major factor responsible for susceptibility of trees to spruce budworm attack (Greenbank 1963a). One of the probable conditions influencing the susceptibility of different ages of trees is the presence or absence of staminate flowers (Graham and Knight 1965). These flowers are most abundant on overmature dominant trees and those that are growing under unfavorable conditions. Also, maturity is accompanied by reduced growth and vigor of trees, and increasing crown exposure. As Mott (1963) points out, "The taller the stand and the more open and exposed the fir crowns, the greater the susceptibility, presumably because the microclimate of feeding sites is better and because females are attracted to taller trees and stands".

If the intensity of infestation and the effects of heavy budworm feeding vary with the age and vigor of the stand, what are the possible effects of these factors on parasitoid behavior?

Increased mortality caused by some parasitoids has been attributed in part to heavy production of balsam fir staminate flowers (Dowden et al. 1950). Budworm larvae feeding on pollen are parasitized more than larvae in vegetative buds. Small parasitoids may be able to reach hosts feeding within staminate flowers more easily than they can reach larvae enclosed in vegetative buds. In addition, parasitoids could improve efficiency by limiting their search area to the staminate flower microhabitat.

Blais (1952) has shown that staminate flowers promote larval development. Shortening of the larval period increases chances for survival by decreasing the length of exposure to natural enemies like parasitoids and predators (Greenbank 1963b).

Variability in phenology of spruce budworm and/or host trees can be caused by moderations in microclimate due to stand density or crown closure. Differences between stands in regard to spruce budworm developmental time and tree phenology have been reported by Hanson (1982). Bud burst of immature balsam fir trees was generally earlier than in pole-sized or mature trees. The larger, expanding buds of the young trees exhibited few signs of spruce budworm infestation. Perhaps early or rapid development of these buds caused the larvae to move directly to new needles instead of boring into developing buds. Young larvae on immature trees which are devoid of flower bracts are also known to wander more extensively in search of food (Greenbank 1963b). Bud development in trees in pole-sized and mature stands was slower and webbing at the base of the buds or entrance holes directly into the buds were apparent. Larvae were found most often in or near buds in the older age-class trees. In younger trees, the larvae were more widely distributed.

Although no significant differences in overall percent parasitism of spruce budworm collected from plots of sapling, pole-sized, or mature trees were found, there were variations in occurrences of certain parasitoids among plots and between stand types. For example, the budworm in the mature age-class plots had the lowest overall parasitism by *G. fumiferanae*, with 1.51% of the larvae in one plot and 0.56% of those in the other parasitized.

Shortening the rotation age of fir appears to reduce the number of more vulnerable mature and overmature stands. The effects on parasitoids vary. For example, staminate flowers of mature trees may provide a desirable

food source for budworm larvae and consequently readily locatable host material for parasitoids. On the other hand, rapid development of larvae which ingest pollen reduces the length of their availability to parasitoids. In some stands, the microclimate of the more exposed fir crowns favors budworm attack. Parasitoid response to moderations in microclimate depends on the species of parasitoid we are considering, the phenologic response of the tree, stand density, and other factors.

Break Continuity of Extensive Mature Forests and Optimize Spatial Diversity of Different Even-Aged Stands

Extended areas of balsam fir are susceptible to spruce budworm outbreaks (Graham and Knight 1965). When a balsam fir monoculture is coupled with high stand density, additional problems arise.

Survival of small larvae increases under these conditions because dispersal loss is relatively low in dense stands of preferred host trees (Morris and Mott 1963). Mott (1963) points out that survival of small larvae is a less important determinant of population trend than survival of large larvae and dispersal of adults. However, he concludes that mature fir stands that are open enough to provide lateral crown exposure (favorable for survival of large larvae) but not so open or so high in non-host content as to make small larval dispersal difficult provide optimum conditions for survival of both these age classes of spruce budworm.

The position or exposure to light of individual trees in a stand can make them unequally susceptible to attack by spruce budworm, and, as discussed earlier, can affect the spatial distribution of parasitoids. As stand density increases, vulnerability tends to increase, perhaps due to reduced vigor and poorly developed crown in dense stands. Simmons et al. (1975) reported that when tree density increases, regardless of species, parasitism rates decrease.

Parasitism increases as the diversity of tree species increases (Kemp and Simmons 1978). Simmons et al. (1975) remarked that parasitizing other insects is only one of several preoccupations of the adult parasitoid. Needs for food, water, and shelter must also be met. It is frequently the case that unbroken balsam fir forests do not help in satisfying these requirement because of lack of diversity of habitat.

Flexner et al. (1983) speculate that "attaining a regulated, sustained-yield forest with equal areas represented by the various age classes should reduce the overall level of forest damage". Providing a variety of age classes of trees enhances the availability of

diverse habitat for parasitoids. Some species of parasitoids are conspicuously more frequent in one age class stand than another. Others occur irregularly in budworm throughout a stand of a uniform age. Still others show no differences in their appearance, regardless of the age of the trees. Breaking up the continuity of extensive areas of mature forest creates openings which reduce the possibility that dispersing small larvae will land in suitable sites (Mott 1963) and provide favorable and diverse habitats for natural enemies of the spruce budworm (Flexner et al. 1983).

Remove Fir from the Stand and Convert to Less Susceptible Species

The spruce budworm feeds primarily on balsam fir and white spruce, but will also attack red and black spruce (*Picea rubens* Sarg. and *P. mariana* (Mill.)), eastern hemlock *Tsuga canadensis* (L.) Carr., larch *Larix laricina* (Du Roi) Koch, and white pine *Pinus strobus* L. Where mortality to balsam fir has been complete or nearly complete, white spruce trees in the same stands have generally survived the budworm outbreak (Greenbank 1963c). Spruce budworm infestations in pure stands of white spruce have sometimes persisted for long periods without spreading or gaining momentum (Morris 1958). The phenologies and foliage qualities of the three species of spruce make them more resistant to the budworm (Greenbank 1963c).

Female spruce budworm moths show a strong ovipositional preference for undefoliated hosts (Greenbank 1963c). They prefer to oviposit on relatively new needles and on shoots with closely-spaced needles. As defoliation progresses, these preferred sites become increasingly scarce on balsam fir. Loss through dispersal of adults and small larvae increases as the balsam fir dies and the budworms seek new needles.

Emergence of overwintered spruce budworm and bud burst of balsam fir are closely synchronized. Peak emergence of spruce budworm precedes bud burst by only a few days. Later opening of buds on the spruces, most notably the black spruce, results in a certain amount of immunity to budworm damage (Blais 1957).

Budworm larvae are known to feed on old foliage and buds of the red and black spruce during the lag between their emergence and bud burst (Greenbank 1963c). Old foliage and unopened buds do not provide nutrients for satisfactory development of the larvae. Thus, an increased spruce component in the stand may increase the period of host availability to the parasitoids.

Because white spruce shoots grow significantly larger than balsam fir shoots and provide more food per unit of population, they

suffer less damage than balsam fir (Greenbank 1963c). Fye (1963) reported that spruce budworm prefer white spruce during periods of endemism and suggested that these trees may be major food reservoirs at this time. This low-density residual pest population provides a food source for a low-density residual parasitoid population which can rapidly expand its sphere of influence in the event of a pest population increase. Also, larger populations of predators are believed to inhabit white spruce trees than balsam fir trees and these may appreciably reduce the populations of eggs and small larvae (Fye 1965).

Maintain Mixed-Species Composition

As the proportion of non-host tree species in the stand increases, the vulnerability of spruce and fir to spruce budworm tends to decrease. Stands with balsam fir comprising at least 50 percent of the basal area are among the most vulnerable to the budworm (Flexner et al. 1983).

With the exception of A. fumiferanae, G. fumiferanae, Phaogenes hariolus (Cress.), and possibly Horogenes cacoeciae (Vier.), all spruce budworm parasitoids are suspected or known to require an alternate host to complete development (Miller 1963). If a second generation parasitoid requires a different host, the size of the parasitoid population is partly regulated by the least abundant host (Graham and Knight 1965). For a parasitoid requiring an alternate host to be abundant during an outbreak, the alternate host must also be populous (Blais 1965). Alternate host populations limit parasitoid effectiveness and partially account for the variation in parasitism noted in different spruce budworm outbreaks (Miller 1963). A collapsed spruce budworm population can act as the high limit on the parasitoid's potential.

Some parasitoids have the ability to feed on more than one host (i.e., they exploit alternative hosts). This capacity is beneficial during the collapse period, when the parasitoid can turn to other hosts and not suffer from food shortage.

Several parasitoids reared from endemic populations have also been reared from other members of the spruce-fir defoliator complex, indicating that these hosts may serve as reservoirs for spruce budworm parasitoids (Fye 1963). McGugan and Blais (1959) found that the parasitoid Sarcophaga aldrichi Parker, which is a dominant parasitoid of the forest tent caterpillar Malacosoma disstria Hbn. in Ontario, was able to respond to fluctuations in tent caterpillar and spruce budworm populations by alternating between the two.

Nectar or pollen sources are frequently required to sustain adult parasitoids (Coppel and Mertins 1977). I. conquisitor is a

more effective parasitoid of spruce budworm in mixed stands with lower densities of spruce and fir than in pure stands of either spruce or fir. This is attributed to a greater variety of alternate hosts and flowering vegetation which the less dense forest provides. The proximity of these food sources to suitable host insects increases the chances of parasitism by retaining the parasitoids in the stand (Simmons et al. 1975). Nyrop and Simmons (1982) found that adult G. fumiferanae feed in the forest canopy. Forest composition had no influence on this parasitoid's ability to secure food however, and there were no differences in longevity in G. fumiferanae from stands that were exclusively balsam fir and those from stands that were a mixture of balsam fir and other coniferous and deciduous trees.

In periods between outbreaks, the spruce budworm appears to be extremely scarce (Greenbank 1963a). Maintenance of mixed-species composition provides, in some cases, a better habitat for a residual parasitoid population that will exhibit positive rapid density responsiveness to budworm population increases.

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APPROPRIATE SILVICULTURE

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Silvicultural options suitable for reducing the vulnerability of spruce-fir forests to spruce budworm damage are discussed. The concepts of susceptibility and vulnerability are outlined, and a comprehensive list of selected references for further study is presented.

The subject of my talk is supposed to be appropriate silviculture. Webster defines the adjective "appropriate" as suitable, fit, or proper. Webster also defines the verb appropriate as meaning "to steal". Since most of what I have to say is far from original with me, perhaps both definitions are apropos.

The adjective appropriate, of course, has to be qualified by the questions "for what" and/or "for whom". The previous three speakers have discussed at some length the effects of forest stand conditions as factors influencing the mortality rate of spruce budworm in its various life stages. The enhancement of these factors by the manipulation of stand conditions is silviculture designed to reduce the susceptibility of forest stands to attack, and is also related to those forest attributes that support a given population level. Silviculture designed to reduce the vulnerability of forest stands calls for manipulating stand attributes or characteristics that determine the loss of tree growth and mortality that will result from attack at a given level. The concepts are interrelated insofar as susceptibility determines the severity of attack and hence the potential damage.

Silviculture designed to enhance mortality factors of budworm may or may not be compatible with that designed to reduce the probability of damage, and it is probable that neither is totally compatible with silvicultural techniques designed to optimize the production of wood products. In practice, there will be compromises influenced by the perceived or documented efficacy of the proposed silvicultural treatments, their compatibility with one another, and the ultimate objective of the land manager for a given forest stand.

In this paper I discuss silvicultural tactics designed to reduce vulnerability on a stand by stand basis rather than large scale regional strategies that might be put into play. Emphasis is on producing wood products while minimizing growth loss and mortality due to spruce budworm. A word of caution: changing the forest through silviculture will not control the insect because factors such as climate, the dynamics of the natural enemy complexes and the mobility of the insect itself also affect budworm survival.

Long-Term Silvicultural Tactics

The Eastern Spruce Budworm Research Work Conference held in Orono, Maine, this winter, included a workshop on silviculture and the spruce budworm. Invited speakers were foresters active in silvicultural pursuits for a number of large land managing companies. Many of the questions they were asked to address pertained to their "gut" feeling about silviculture as a tool to alleviate budworm damage in both the long and short term. Silvicultural practices they were involved in ranged from site preparation and planting to precommercial and commercial thinnings, and partial harvests, shelterwood harvests, and clearcut harvests. Nearly all were pessimistic about the value of intensive silviculture as a tool to alleviate the impact of budworm. For the most part, however, their experience with intensive silvicultural techniques was short term, not always perceived as part of an overall "package" of integrated pest management that includes direct control, and initiated in the teeth of a raging epidemic.

One gets the impression that researchers in budworm silviculture are optimistic about its efficacy, while foresters on the ground are the pessimists. Part of the problem is that most espoused silvicultural goals are based on working hypotheses, not proven concepts. Our experience in shaping stands and forests toward derived goals over the long term, perhaps a rotation, has been limited if not nonexistent. As a result, the expected reduction in vulnerability cannot be quantified precisely. The state of our knowledge about the dynamic interaction between the budworm and the forest is such that we can make only qualitative statements. However, it makes sense to proceed at the qualitative level using the logic of the vulnerability relationship.

Despite the previous statement, most silvicultural tactics have been proposed from efforts to relate budworm-caused tree mortality to stand characteristics both in

a qualitative and quantitative manner. In recent reviews of the many attempts to correlate vulnerability with stand characteristics, MacLean (1980, 1982) concluded that only one general association appeared to be consistent--mature or overmature stands with a high proportion of balsam fir tend to be the most vulnerable.

Both mortality and growth loss are functions of the timing and intensity of defoliation. However, predicting mortality and growth loss from stand characteristics is not a precise science. This is understandable because budworm populations respond to biological and meteorological factors that are often independent of stand condition. The intensity, duration, and protection history of budworm outbreaks are important factors.

Where extremely high populations are present, silvicultural techniques will only partially alleviate the total impact of the infestation, mainly by altering the timing and pattern of mortality and growth loss.

Although stand characteristics other than age and the proportion of balsam fir are not closely related to damage from spruce budworm, they have exhibited local importance. Factors such as stand structure, density, crown exposure, tree vigor, and the proportion of nonhost species have shown a relationship in specific instances.

With all of these caveats, one must proceed on a combination of faith and logic, a dollop of scientific evidence and conclusions drawn from experience. In our favor is the fact that most of the silvicultural procedures recommended to reduce the risk of budworm damage are the same recommendations in an intensive silvicultural program for optimum growth and yield, the possible exception being stand conversion to a nonhost species.

At the root of all silvicultural recommendations are the well-known differences in vulnerability among the various host species. Balsam fir is the species most vulnerable. Mortality of fir usually begins 5 to 7 years after the onset of a severe attack, and mortality in mature or overmature stands can reach 100 percent. Mortality in immature stands and in spruce stands is more variable, but can be as high as 70 percent. Figure 1 shows average levels of tree mortality of fir and spruce in mature stands (more than 50 to 60 years old) and immature stands. Figure 2 shows examples of actual mortality patterns over time.

White spruce usually is considered the second most vulnerable species. White spruce can support populations of budworm as high as those supported by balsam fir, but they sustain less damage because they produce more and larger shoots, thus supplying more food for feeding larvae.

Red spruce and black spruce in that order are the next most vulnerable species. Their relative resistance is due mainly to late opening buds--on the average, red and black spruce open 13 days after balsam fir and 9 days after white spruce. Black spruce foliage is also less hospitable to budworm as a source of food.

In some situations, the budworm will feed on eastern hemlock, eastern larch, and eastern white pine. Hemlock is particularly susceptible to damage, and there have been instances of topkill and mortality. Hemlock foliage also supports a sizeable number of spruce budworm egg masses.

Most studies have shown that stand vulnerability increases with increasing amounts of mature or overmature fir. Additional trends evident in various studies indicate that:

1. Vulnerability of spruce and fir decreases as the proportion of nonhost species in the stand increases. If spruce and fir are in a subordinate crown position, this trend apparently is enhanced. It is especially apparent in stands of understory or intermediate spruce and fir overtopped by aspen such as is found in the Lake States and occasionally in northern New England; a spruce-fir understory in a pioneer hardwood stand; or individual spruce or fir trees overtopped by paper or yellow birch.

2. Fast-growing, full-crown trees that reflect good site quality and growing conditions are less vulnerable to damage than trees under stress.

3. Vulnerability tends to increase as stand density increases. This higher vulnerability may be related to a lack of vigor and/or poorly developed crowns in dense stands, or to differences in larval dispersal dynamics. However, in a few recent instances where density has been reduced in spacing operations, budworm damage has been severe.

4. Individual spruce-fir trees in a subordinate crown position relative to other host trees are more vulnerable to damage primarily due to downward larval dispersal and their poorer vigor relative to overstory trees.

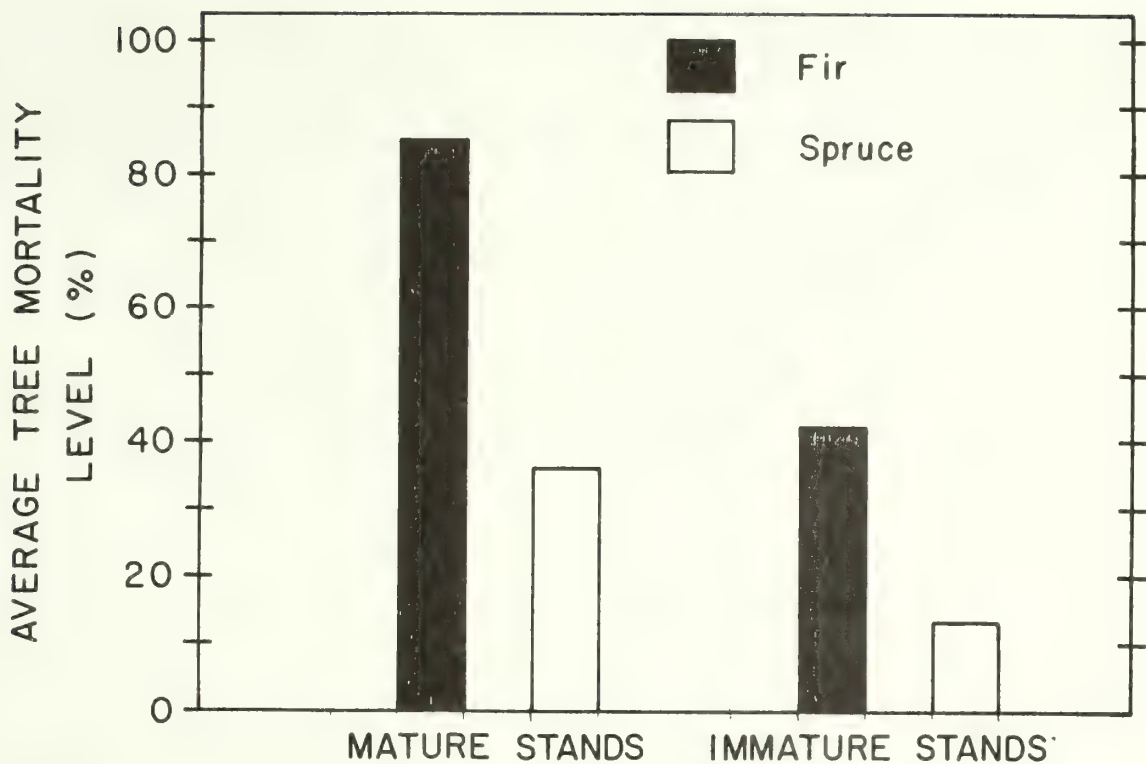


Figure 1.--Average levels of mortality of balsam fir and spruce in mature and immature stands (From MacLean 1980).

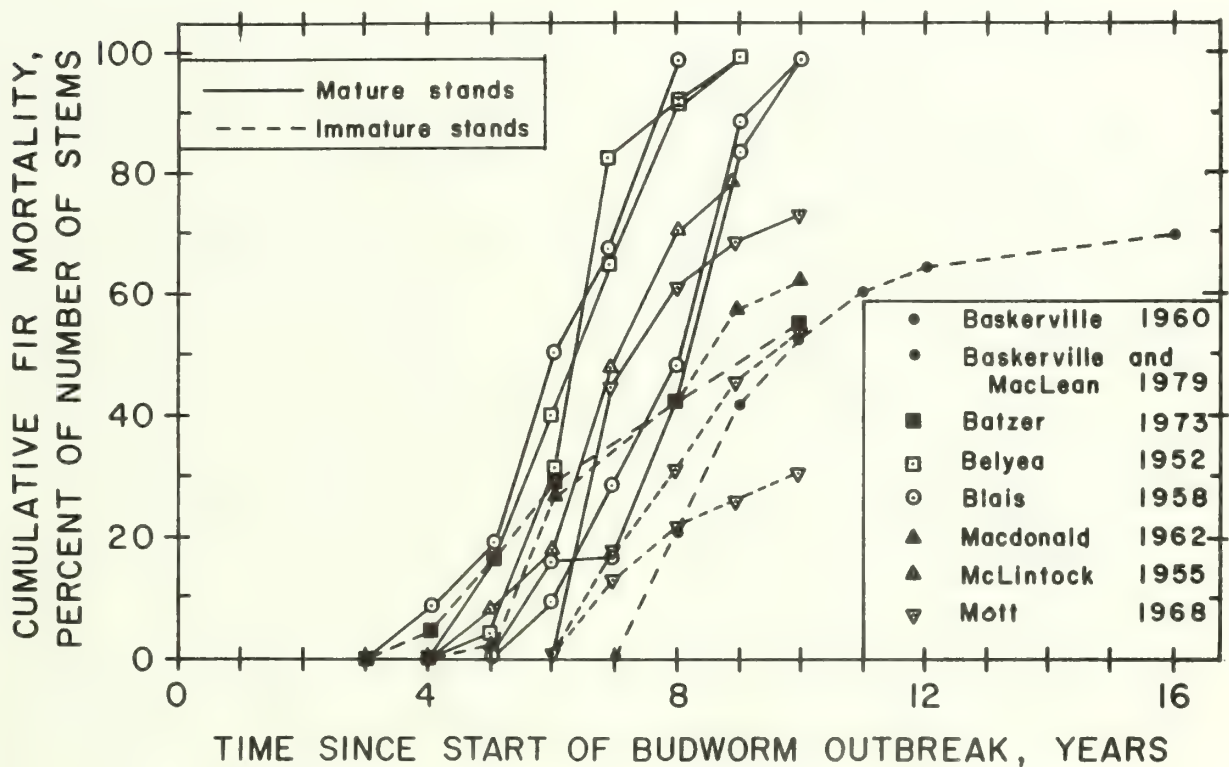


Figure 2.--Cumulative fir mortality in relation to time during various spruce budworm outbreaks (MacLean 1980).

Silvicultural Goals

These relationships between stand characteristics and vulnerability to budworm damage, while quite general in nature, suggest the following silvicultural goals: 1) maintaining a vigorous stand with rapid growth rates, 2) increasing the spruce and/or nonhost component in the stand, and 3) reducing the fir component in the stand at an early age. Achieving these goals should provide a general reduction in stand vulnerability, particularly for future infestations.

In the absence of budworm damage, the end result of such stand manipulation is the production of high-value wood products and the maintenance of a vigorous forest cover. But we know that there is a high probability of a severe infestation occurring at least once in the rotation of a spruce-fir forest regardless of an intensive silvicultural program, and it is natural to ask what additional benefits might be derived from reducing vulnerability.

Well-managed stands should respond better to protection efforts as they usually are well spaced and vigorous. Species compositions should be favorable. Having a sizeable proportion of land in a relatively invulnerable condition should allow more time between direct control efforts, should decrease the need for direct control in the early stages of an infestation, and should allow more time for shifting salvage operations to the most vulnerable stands as mortality commences. Also, the glut of salvaged wood that occurs at the height of an infestation should be reduced somewhat.

Silvicultural Treatments To Meet These Goals

How can managers reduce vulnerability? From a regional standpoint the magnitude of the undertaking is overwhelming. Nevertheless, silvicultural treatment of selected stands is a viable and important weapon in the integrated pest management arsenal. Given both sufficient time and intensity of treatment before a severe infestation, managers can achieve significant reduction in vulnerability, and any silvicultural treatment of forest stands should be considered in light of its long-term effects on vulnerability to the budworm.

When evaluating intensive silvicultural options a number of factors must be considered. Site productivity, accessibility, and present stand condition probably are the most important factors common throughout the range of spruce budworm. Differences in marketing, economics, and social factors throughout the budworm range also should be considered. Obviously, the availability of information sources such as inventory data, type maps, and data on site productivity are important aids for identifying stands worthy of intensive silvicultural input. The greatest opportunity for manipulating species composition of existing stands is a high-quality, accessible site. Fully mature or overmature stands with a good proportion of spruce or nonhost species probably require the least investment because of marketable products removed, but sapling and pole stands offer the best opportunity because of a greater number of stems to choose from, generally greater vigor, and somewhat greater resistance to windthrow.

Because of the relative tolerance to shade of the spruces and balsam fir, both uneven-age and even-age management is appropriate, depending on the circumstances (Table 1). However, even-age management is the most common practice in use today throughout the range of spruce and fir.

Table 1.--Summary of even-age and uneven-age forest management systems to reduce vulnerability to spruce budworm damage

Even-Aged Management Systems

- Clearcut harvesting in blocks or patches
- Clearcut harvesting in strips
- Shelterwood harvesting

Components of system

- Species conversion--natural conversion to less vulnerable species or site preparation and planting to nonhost or low-vulnerability species.

- Thinning and partial cutting--heavy discrimination against fir where possible to encourage increases in spruce content.

Uneven-Aged Management Systems

- Individual tree selection harvesting
- Group selection harvesting

Even-age silvicultural systems.--

Clearcut harvesting in blocks, patches, or strips is recommended for mature, overmature, or insect- and disease-ridden stands where partial harvesting could result in mortality or damage to residual trees. Clearcutting is an efficient system of harvesting, especially with highly mechanized equipment.

Natural regeneration often can be used to restock a clearcut area. However, success is critically dependent on the presence of advance regeneration. Biologically, a clearcut harvest with advance regeneration present is a shelterwood, but there is no attempt to manipulate the size or species composition of the regeneration by means of preparatory harvests as there usually is in the case of the shelterwood system of silviculture. In smaller clearcut blocks, patches, or narrow strips, where adequate advance regeneration is absent, seed dispersal from adjacent stands may suffice, but in many cases will require site preparation and planting. Residual overstory trees of spruce budworm host species must be removed to prevent budworm larvae from dispersing downward to the new regeneration.

In many areas, clearcut harvesting encourages undesirable vegetation such as hardwoods and raspberries that may inhibit growth and development of softwood regeneration. Herbicide treatment of these areas will be necessary if normal growth and development is expected.

Clearcut harvesting in narrow strips or small patches often is termed strip or patch shelterwood. As mentioned previously, it is used where regeneration is lacking, but it also is a valuable technique when excessive losses of regeneration to exposure or mechanical damage are anticipated. Both methods leave nearby border trees that provide a seed source for regeneration and partial shade. However, these same border trees are a potential source of spruce budworm larvae that may disperse to young seedlings. Harvesting in strips or patches increases the species diversity of plants and may encourage natural enemies of the spruce budworm.

The shelterwood system is applicable to spruce-fir stands that lack adequate advance regeneration. It is especially suitable for stands on good sites where vigorous growth can be expected, windthrow potential is minimal, and there are no insect or disease problems of immediate concern. With the shelterwood system, the overstory is removed gradually in two or three stages, thus stimulating seed

production and providing light and moisture conditions conducive to seedling development. Gradually opening the stand may improve windfirmness, and the partial shade will reduce the development of herbaceous growth such as raspberries.

The shelterwood system allows good control over species composition of the developing regeneration so long as desired species are represented in sufficient numbers in the overstory. An additional benefit of the system is the good growing conditions provided the residual overstory, which should be high quality, vigorous trees. However, if high populations of spruce budworm are present in the overstory, direct suppression of the insect will be required to ensure seed production and to protect developing regeneration.

Stand conversion.--The economic and biological ramifications of stand conversion and the creation of monocultures are many and vary considerably across the range of the spruce budworm. Throughout most of the spruce-fir region there have been numerous recent advances in site preparation, planting techniques, improved planting stock, and techniques for controlling competing vegetation. Although relatively expensive, planting to a nonhost or relatively invulnerable host on the best sites certainly will decrease vulnerability and susceptibility to spruce budworm and improve long-term yield potential. Of the host species, black spruce is the most promising.

Uneven-age silvicultural systems.--

The individual tree and group selection systems of silviculture have been recommended for reducing vulnerability to spruce budworm damage. Repeated light harvests create stand openings that favor the establishment of regeneration. Because these harvests take place in all merchantable size classes, they can be an effective tool in altering species composition. The main disadvantage of the selection system is that a continuous, open canopy consisting of mature or nearly mature trees that are both relatively vulnerable and susceptible to spruce budworm is maintained. Once infested, the overstory serves as a reservoir of larvae that disperse downward, exposing trees in smaller size classes to damage. The selection system also is more complicated than most even-age systems because of the mixture of age and size classes and the need to maintain this mixture at specified levels. Harvesting must cover a larger area to meet a given allowable cut, damage to residual trees is a greater risk, marking trees in advance usually is

necessary, and detailed record keeping is desirable. However, the selection system is the only way that owners of small properties can get a consistent return over time; in some areas such as streamsides and roadsides where esthetics are important, the selection system is the only viable alternative.

Thinning or partial cutting.--If the regeneration process has resulted in maintaining or increasing spruce (particularly red and black spruce) or nonhost species, the key to reducing vulnerability is a program of frequent, relatively light partial harvests or thinnings. This will allow the alteration of species composition to the detriment of fir. A precommercial thinning when the stand reaches the sapling or small pole stage can cause a dramatic change in the species composition of the residual stand. Even a small proportion of well-distributed spruce may be sufficient in absolute numbers to generate acceptable stocking if it can be freed from the fir competition.

Besides removing fir, the primary goals of partial harvests should be to: 1) provide adequate growing space for individual trees, 2) remove trees that may not survive to the next harvest, and 3) avoid creating large holes or openings in the canopy that may decrease windfirmness. Removing trees in a subordinate crown position should be the first priority, followed by improving spacing in the main canopy.

The potential for wind damage after a partial harvest varies considerably according to site and soil characteristics, the amount of overstory removed, and the past management of the stand. Harvests should be relatively light (perhaps no more than one-third of the basal area removed). If past management has kept the stand vigorous, well spaced, and fast growing, improvement in windfirmness should follow. The windthrow history of an area, if available, might provide a clue to future potential. It is possible that budworm defoliation and subsequent rootlet mortality may be a factor increasing the risk of wind damage. Of course, the possibility of an overpowering storm, regardless of stand condition, is always present.

This has been a very brief discussion of silvicultural possibilities to alleviate budworm damage. Details of each recommendation can be found in the references listed. Much is still "art" rather than science. As we are better able to quantify the reduction of

vulnerability, it is hoped that we will be able to recommend specific actions, at specific levels, at specific times and for specific forests and budworm conditions, that will render future budworm outbreaks less potent by specific amounts.

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TREE IMPROVEMENT POLICY GUIDELINES FOR ONTARIO
WITH SPECIAL EMPHASIS ON WHITE AND BLACK SPRUCE

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Currently under review is the Ministry of Natural Resources' first comprehensive document on the Policies and Strategies of Tree Improvement for the Province of Ontario. It describes the rationale for needing tree improvement, the history of the research and management programs, some basic principles, species priorities for improvement, recommended approaches for the various species, organizational responsibilities, and an example of economic costs and anticipated returns. The document is intended to serve many purposes. It outlines the various tree improvement work that is required to supply the artificial regeneration program with sufficient seed and planting material, it provides guidelines and direction to the field specialists who will be writing the tree improvement management plans, and most important it provides senior managers with sufficient information to enable them to determine the level at which they are willing to support and fund the program.

This paper will summarize parts of the document with special emphasis on white and black spruce as well as provide some background information on the Province of Ontario.

Introduction

Ontario is a forested Province. The total land area is 96.9 million hectares (374,000 square miles). Productive forest area is 42.5 million hectares (164,000 square miles) or 42 per cent of the total and commercial forest area is 33.5 million hectares (129,430 square miles) or 35 per cent of the total. The Crown (government) owns 88 per cent of the land and the private sector 12 per cent. However, the northern portion is very different from the southern. Ninety-two percent (28.7 million ha) of the north is Crown land compared to only 27 percent (642,000 ha) in the south. The north is composed of extensive continuous forests in the Boreal Forest Region; whereas the south, in the Great Lakes - St. Lawrence and Deciduous Forest Regions, is heavily populated, highly industrialized and the rural areas primarily farmland interspersed with small woodlots. In 1981-82, 17.5 million cubic metres (4.03 million cords) were cut, of which 14.6 million (4.03 million cords) were softwoods; but by the year 2020, the annual cut is expected to be 25 million cubic metres (6.90 million cords). Economically, forestry is the prime industry in the Province and employs approximately eight and a half per cent of the working population.

The Government of Ontario has made a commitment to maintain the productivity of the province's forests by regenerating the cut and burned productive forest areas. This commitment complements one of the purposes of the Forest Management Agreements. With the advent of these agreements, started some five years ago between the Ministry and forest industry, the areas being regenerated have increased at a dramatic rate and the number of seeds and the number of trees required annually have risen and will continue to rise exponentially until the 1990s. If the production targets are to be met and the predicted wood shortages minimized, more support is needed, not only for silvicultural management, but also for all aspects of the tree improvement program. This latter need has been recognized by both the Ministry of Natural Resources and by several forest companies, who recently joined together to establish the Ontario Tree Improvement Council.

Given the size of Ontario's artificial regeneration program and the investment in stock production, site preparation, and planting, it is advantageous to use only genetically improved material. To obtain the greatest possible return from the money invested, tree improvement must be integrated with silvicultural management. In well-managed stands grown from seed produced in a tested and rogued first-generation seed orchard, volume gains of 10 to 15 percent are easily attainable. Substantial and impressive volume gains can also be obtained from accurate site selection and good stand management, but once obtained, these gains cannot be increased; whereas continual gains are possible through progressive breeding, testing, and selection for advanced-generation orchards. To maximize any return on tree improvement and silviculture; time, money, and manpower should first be concentrated on the best sites.

Several economic analyses, including one later in this paper, have shown that major tree improvement programs can be justified by increases in volume growth as low as 3 or 4 percent. The projected gains for the proposed strategies in this paper far exceed three percent. Moreover, through planning and through the use of new technology, the time from initial investment to the initial return on investment can be shortened. For example, genetic gain can be captured more rapidly and efficiently for those species that can be propagated through the rooting of cuttings rather than by using conventional production seed orchards. Breeding halls can reduce the time from the establishment of an orchard to the onset of flowering, thereby significantly reducing the time needed to establish progeny trials and to obtain parent donor material for the cutting programs.

In order to improve the quality of wood and to increase the yield through tree improvement, it is important to have both short-range and long-range goals. In the short term, some genetic gain can be obtained relatively quickly and

economically. Such gains are significant when there is a large artificial regeneration program. But to get the maximum benefit from genetics, there must be a continuing program with long-range goals. To reach these goals, much planning and forethought are necessary, especially since the plant material initially selected for the program will constitute the foundation for future generations of trees.

Tree improvement within any organization is a continuous, long-term venture that requires continuity of support, funding and staffing. Goals must be decided at the outset, the necessary funds committed, and the program started as rapidly as possible. Delays in getting started mean delays in reaping the benefits as well as a depletion of the gene pool with which to work.

History and Current Status of Tree Improvement in Ontario

Research on tree improvement by the provincial government was pioneered by the then Department of Lands and Forests in 1946 with Dr. Carl Heimburger. The early studies dealt with aspen, white pine, and hard pines; spruce studies were started in the mid-1960s with Dr. Don Fowler. The spruce work at first concentrated on interspecific hybridization, but in the early 1970s there was a shift towards intraspecific hybridization to evaluate the plus-tree selections. Through these years there was also much experimental work on the rooting of the spruces.

During the late 1970s and into the 1980s, the work expanded to include physiological and quantitative genetics and shifted away from the conventional "tree breeding". Various projects examined the genetics of frost resistance and drought tolerance, identified and evaluated genetic variation through isoenzyme analysis, studied methods of flower induction, and determined the most effective and efficient mating and test designs.

Operational tree improvement started about ten years after the research. During the late 1950s modest programs for the selection of plus-trees were started for several species including white and black spruce. Scions were collected and grafted for the establishment of clonal production orchards. Unfortunately, the success rate of much of the early grafting was very low. In addition poor site selection and inadequate management of the first seed orchards led to high mortality in the outplanted stock. Not until the mid-to late 1970s was a concerted effort made to improve the results. The slow development of the grafted orchard program was one of the reasons for switching to seedling seed orchards for the first generation of black spruce work.

Since 1980, there have been some important changes in emphasis. These have included specific strategies for each of our important species, a major thrust in establishing all production and

breeding orchards within a few years, publishing operational guidelines for all aspects of the tree improvement program, and intensive training for field staff culminating in the tree improvement policy document.

Species Priorities

The choice of species for a tree improvement program is based on a number of factors. The primary one is the commercial importance of a species as this determines the size of the areas harvested, and in turn plays a major role in the size of the artificial regeneration program needed. Two other important factors are the genetic variability of the species and the heritability of the characteristics for which improvement is desired.

The priorities differ from one portion of the Province to another. The overall Provincial priorities, in order of importance, are black spruce, jack pine, white pine, white spruce and hybrid poplar. Lower on the priority list, but still significant enough to merit intensive tree improvement strategies, are tamarack, black walnut, European x Japanese larch, Norway spruce and silver rust-resistant hybrid white pines.

Other hardwoods such as the aspens, maples and yellow birch are not considered priority species for improvement as regeneration is primarily by natural means. For this reason, the emphasis should be on good stand management to ensure high quality regeneration, optimal stocking, and the maintenance of a satisfactory gene pool. Only small quantities of this group of species are planted and survival in many of the plantations is very poor. Until good silvicultural management can be practised and until the planting program warrants, tree improvement cannot be economically justified.

Although red pine still plays a large role in Ontario's artificial regeneration program, there is no strategy proposed because the amount of genetic variation is minimal. Any attempt to improve the species would not be cost-effective.

Over the past thirty years there has been a significant shift in the demand for white and black spruce. Figure 1 shows the change in numbers of seedlings grown over time for these two species. Figure 2 shows the percent change for the same time period. There are several reasons for the increased interest in planting white spruce, at the least of which is the occurrence of spruce budworm and the damage caused by this insect. Two other common problems associated with white spruce are damage from late spring frosts and retarded growth due to "planting check". The ease of raising black spruce, both as container and bare-root stock; in addition to high degrees of successful plantation establishment, especially since black spruce is a pioneer species, has led to large numbers being established throughout its commercial range. Conversely, white spruce normally grows in

mixed-wood stands, is better known as a climax species and does not lend itself to being planted on large cut-overs as pure species plantations.

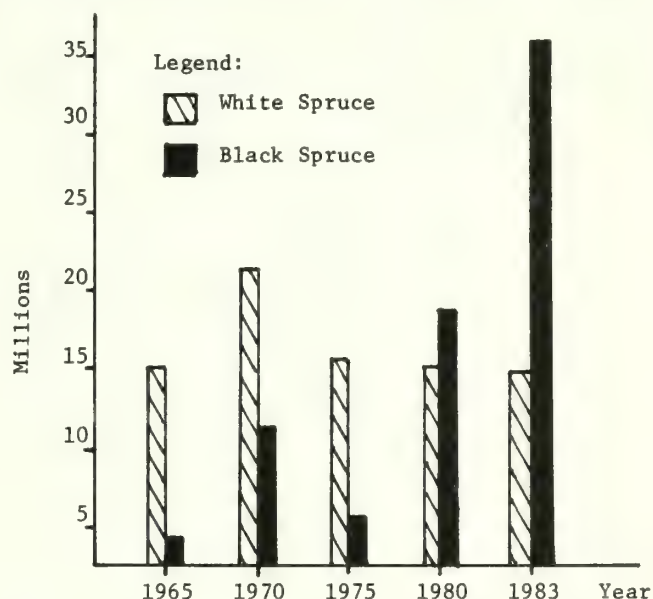


Figure 1: Numbers of black and white spruce trees planted through time.

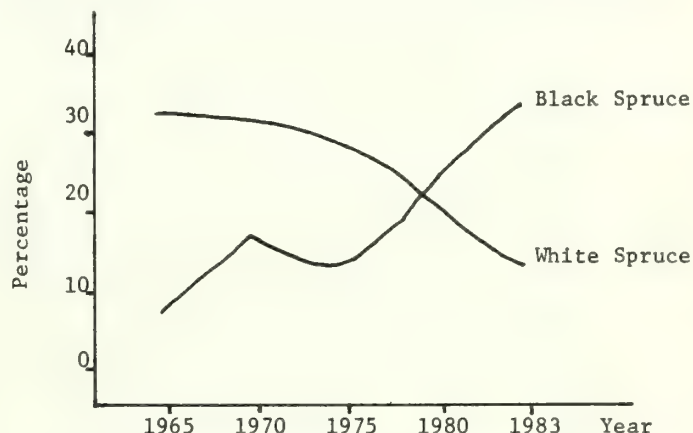


Figure 2: White and black spruce seedling production as a percentage of all seedlings produced.

Tree Improvement Strategies

Through the concerted efforts of quantitative forest geneticists throughout the world, more breeding options are available to the forest manager than ever before. These have been examined and three intensive breeding strategies have been developed for Ontario species. The strategies for

each species depend on a number of factors, including ease of reproduction, either sexually or asexually; ease of scion or seed collection for seed orchards; time from establishing an orchard to the onset of flowering; and ease of cutting production from either hedge orchards or serial propagation. A base program is also proposed for all species artificially regenerated. Only policy guidelines are outlined rather than operational details. The latter will be found in a series of publications that are either published, in press or in the draft stage.

Strategy I - The Base Program

This base program is the minimum work required for all native species that are regenerated artificially, including those that do not merit an intensive tree breeding strategy, either because there is not enough variation in the species or because the regeneration program is too small to justify the establishment of production seed orchards. It will also provide material to the regeneration program for the priority species until seed or cuttings are available from the more advanced breeding programs.

A summary of points in the Base Program follows:

- 1) Seed for all species will come from an identified source;
- 2) Enough seed (or rooted cuttings) will be available for each planting zone so that no material will have to be moved far from its place of origin;
- 3) Neither seeds nor seedlings will be moved from one planting zone to another without permission from the Administrative Region and the Main Office Tree Seed and Forest Genetics Unit.
- 4) Seed will not be collected from plantations unless its seed source is known. If the source is unknown, the plantation must be one-third rotation age before any seed is collected from it;
- 5) All seed-collection and seed-production areas will be in natural stands or plantations whose seed source is known. If the source is unknown, the plantation must be one-third rotation age before being designated as a collection or production area;
- 6) All gene pool reserves and seed-collection and seed-production areas will be regenerated with their own seed source.

Strategy II - The Seedling Seed Orchard

This approach is proposed for species that have characteristics such as poor success in grafting of scions from mature trees, difficulty in selecting phenotypically superior trees in natural stands, and a precocious flowering habit. Black spruce is amenable to this approach for the first generation of selection and improvement.

In the seedling seed orchard approach, superior trees are selected from natural stands in each seed

zone. Open-pollinated seeds are collected from each tree, identified by family and germinated; the resultant seedlings are planted in a production seed orchard and at least two family test plantations. In addition to seed, a few scions are collected from each parent tree, grafted and placed in a clonal breeding orchard. Performance measurements such as height, diameter, and form are taken in the family tests and are used to eliminate the poor representatives in the production orchard, thus improving the quality of seed produced. Some trees from the family test may also be used to establish the second-generation orchard. As the breeding orchard matures and starts to flower, controlled pollinations are made according to a predetermined mating design. The progeny produced are planted in field trials. Although the trials are also used to evaluate the production orchard, their primary purpose is to provide the foundation stock for the second-generation orchards. Figure 3 outlines the steps in this program.

A summary of the points for this approach follows:

- 1) By the year 2000, all seed required for the production of bareroot and container stock will come from first-generation seed orchards;
- 2) The first-generation production orchards will be established with seedlings according to a predetermined layout;
- 3) A minimum of 450 selections will be made in order to obtain the 400 families required for the orchard;
- 4) A minimum of two family tests will be established to evaluate the material in each seedling seed orchard;
- 5) A breeding orchard will be established for all superior trees selected;
- 6) Selective breeding will be done after the first evaluation of the family tests according to a specific mating design;
- 7) A minimum of three progeny tests will be established for each pedigreed family according to a predetermined layout;
- 8) Selections from the family tests and the progeny tests will form the foundation for the second-generation orchards;
- 9) The clonal approach which uses rooted cuttings will be followed whenever economically and biologically feasible, especially in the early stages of seed production in the orchards in order to use the genetically improved seed more efficiently.

Strategy III - The Clonal Orchard Approach

This approach is proposed for species that characteristically occur in mixed-wood, uneven-aged stands necessitating a more expensive, time-consuming superior tree selection method, have good graft compatibility, and a non-precocious flowering habit.

Superior trees are selected primarily from natural stands (occasionally from plantations if not enough natural selections are available)

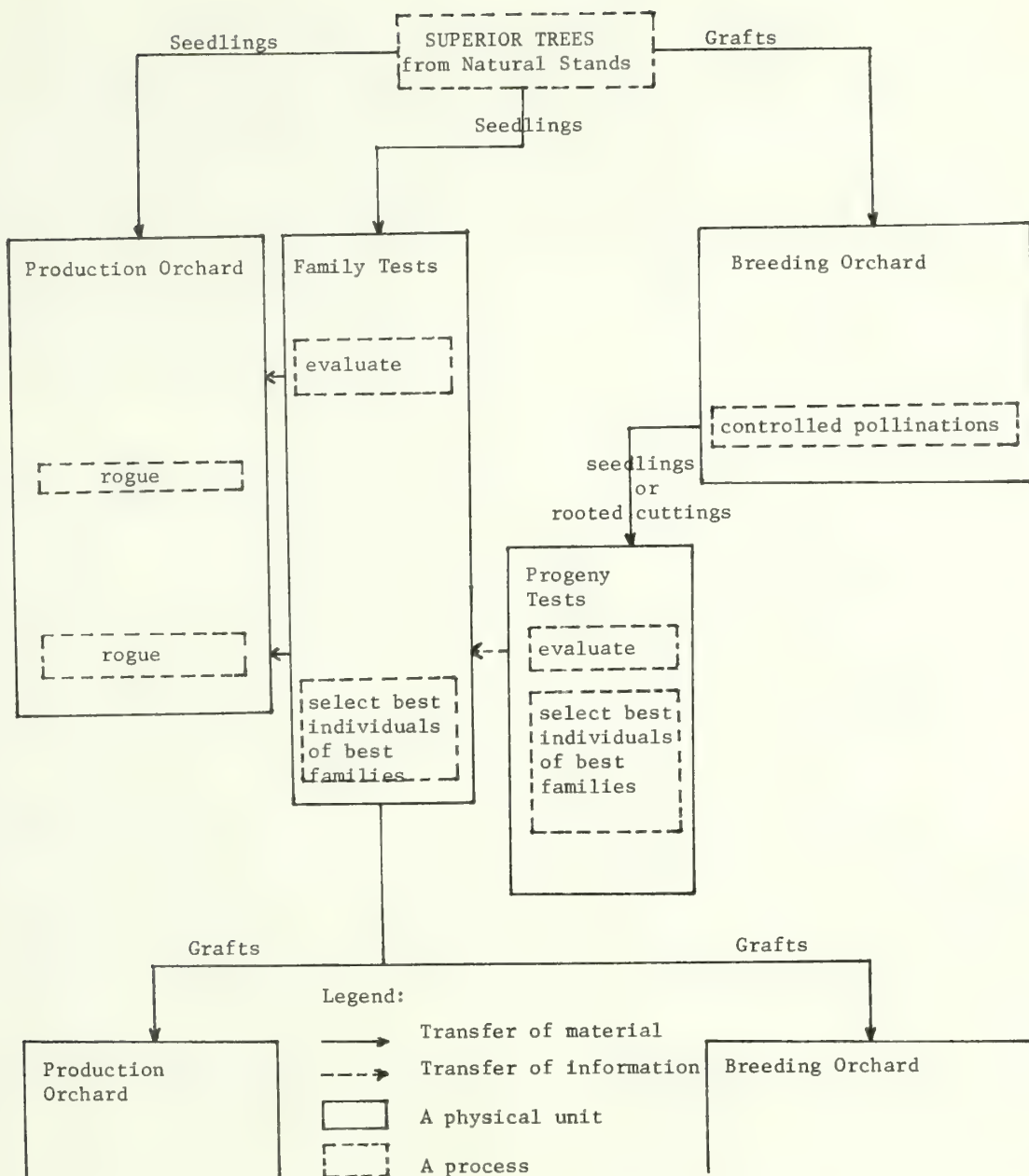


Figure 3: Strategy II - The Seedling Seed Orchard Approach.

in each seed zone. Scions are collected from these trees, grafted and placed both in production orchards and breeding orchards. As the breeding orchard starts to flower, controlled pollinations are made according to a specific mating design. The trials are used first to evaluate the first-generation production orchard and then to provide foundation stock for the second-generation orchard. Figure 4 outlines the steps in this program.

A summary of the points for this approach follows:

- 1) By the year 2000, all seed required for the production of bareroot and container stock will come from first-generation seed orchards;
- 2) The first-generation production orchards will be established with grafts according to a predetermined layout;
- 3) A minimum of 240 selections will be made to obtain the 216 clones required for the orchard;
- 4) A breeding orchard will be established for all superior trees selected;
- 5) Breeding will start with the onset of flowering in the breeding orchard;

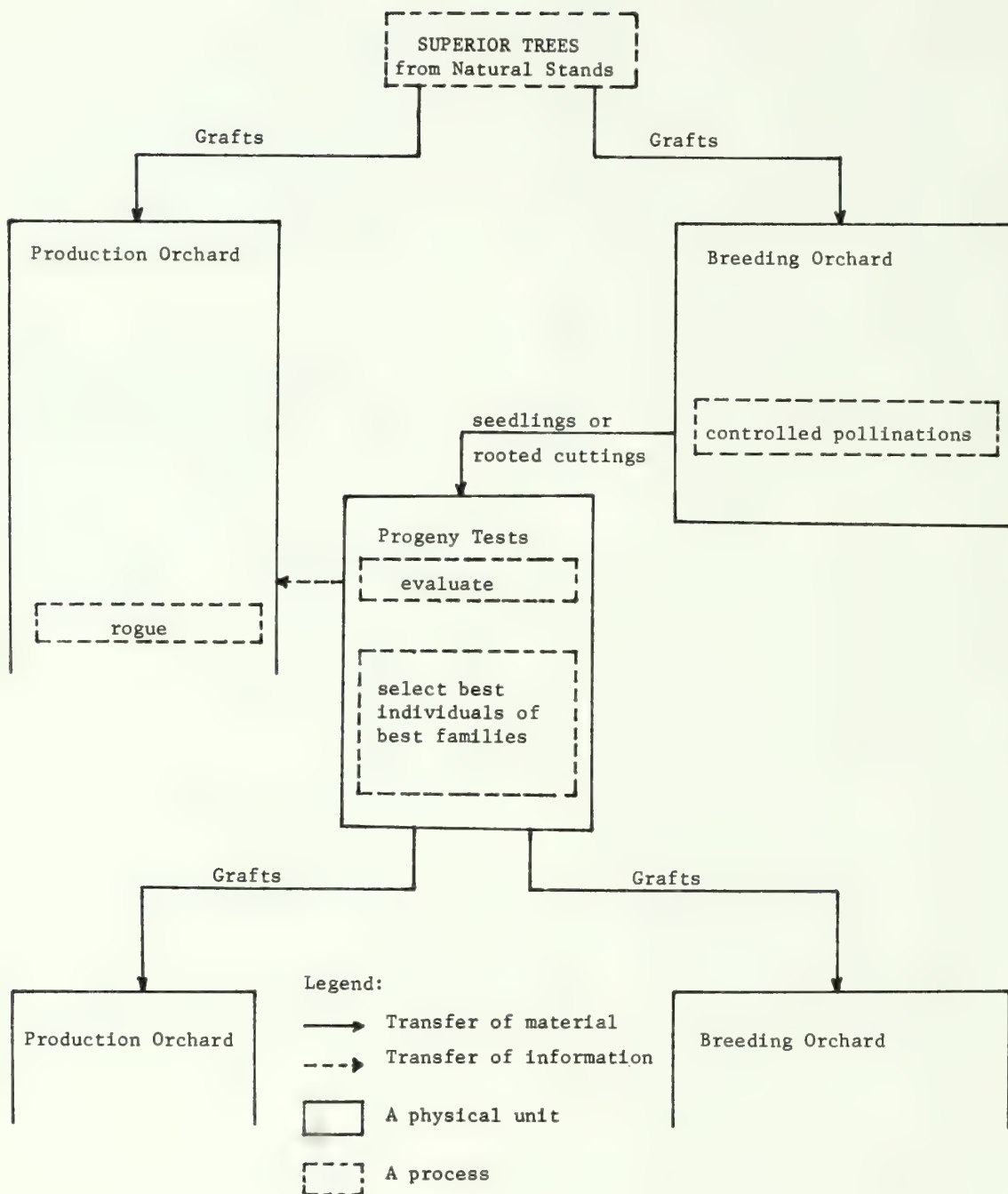


Figure 4: Strategy III - The Clonal Seed Orchard

- 6) A minimum of three progeny trials will be established for each set of pedigreed families according to a predetermined layout;
- 7) Information from the progeny trials will be the basis for roguing the production orchards;
- 8) Selections from the progeny trials will form the foundation stock for the second-generation orchards;
- 9) The clonal approach using rooted cuttings will be used whenever it is economically and biologically feasible, especially in the early stages of seed production in the orchards in order to use the genetically improved seed more efficiently.

Strategy IV - Clonal Forestry

This approach is proposed not only as a source of improved material through the first generation but also as a source of material for all subsequent generations. Clonal forestry is recommended for species that have several characteristics such as ease of rooting, difficulty in being reproduced by seed, insufficient quantities of seed required to fulfil the needs of an artificial regeneration program, too small an artificial regeneration target to merit a conventional production orchard program, or a need to produce specialty stock (eg. blister-rust resistant white pine hybrids).

In the clonal forestry approach for most species other than poplars, superior trees are selected from natural stands, plantations and local or external improvement programs. Scions are collected from these trees, grafted and placed in a breeding orchard. As the breeding orchard matures to flower, controlled pollinations are made according to a specific mating design. The resultant seeds are germinated and the juvenile seedlings are used as parent donor stock for the production of rooted cuttings. Some material is placed in field test plantations and the rest is used for production plantations. After several years of field testing, the best families are identified and their parents are used for selective breeding to produce donor stock for clonal production plantations. The best clones are also selected for these test plantations and put into hedge orchards and in the next-generation breeding orchard. The hedge orchard supplies donor material for production plantations; the breeding orchard is used to make additional crosses for future generation testing and selections. Figure 5 illustrates the steps in the program.

The above approach is modified to accommodate specific characteristics of poplar.

Summary of the points for this approach follows:

The number of trees selected for any particular clonal forestry program will depend upon the source of material and the purpose for which the cutting will be used; Breeding orchards will be established for all selections made; One breeding orchard can contain several breeding zones for each species, several species and several species-hybrids of each species; Breeding will start with the onset of flowering in the breeding orchard; A minimum of three clonal-progeny trials will be established for each set of pedigreed families according to a predetermined layout; Information from the clonal trials will determine which parents will be used for production of additional seed for the donor stock that will supply cuttings for production plantations;

- 7) The best clones will be selected from the clonal-progeny trials for the establishment of hedge orchards and advanced-generation breeding orchards;
- 8) Material for production plantations will be mass-produced either from cuttings obtained in an hedge orchard or by the serial propagation of rooted cuttings;
- 9) Standards for clonal forestry will be established by the end of 1984.

The above four strategies form the basic policy guidelines. The Base Program is used for the priority species until seed is available from the production or breeding orchards, and continues to be used for all other species artificially regenerated within the Province. Strategy II is proposed for the first generation of selection for black spruce and jack pine; strategy III for the first generation of selection for white pine, white spruce and black walnut; a modification of III for tamarack; strategy IV for Norway spruce, European and Japanese larch, blister-rust resistant white pine hybrids, and a modification of IV for hybrid poplars. Strategy IV would also be used with the species mentioned in strategy II and III to supplement the seedling requirement with rooted cuttings.

Strategy for Black Spruce

A summary of the Ontario approach for this species is as follows:

- 1) Strategy I - the Base Program will be in effect until material is available from the seed orchards;
- 2) Strategy II - The seedling seed orchard approach will be used for black spruce;
- 3) All future first-generation production orchards will be seedling seed orchards;
- 4) The collection of cones and scions for all spruce orchards will be under way by 1985;
- 5) The establishment of all production and breeding orchards will be completed by 1990;
- 6) All planting stock (either seedlings or vegetative propagules) will originate from orchard material by 1995;
- 7) Considerable effort should be devoted to developing the clonal forestry strategy;
- 8) Clonal stock should form 30 to 50 percent of the planting requirements by 2000.

To fulfil the planting needs for black spruce, a total of 350 hectares of seedling seed orchards are required for 24 different breeding zones. The projected annual production per hectare of orchard is 0.5 million viable seed at 15 years, 1.0 million at 20 years and 1.5 million at 30 years of age. The anticipated volume gain in seedlings produced from orchard seed is approximately 8 percent from a 15-year old orchard, 11 percent from a 20-year old and 14 percent from a 30-year old one.

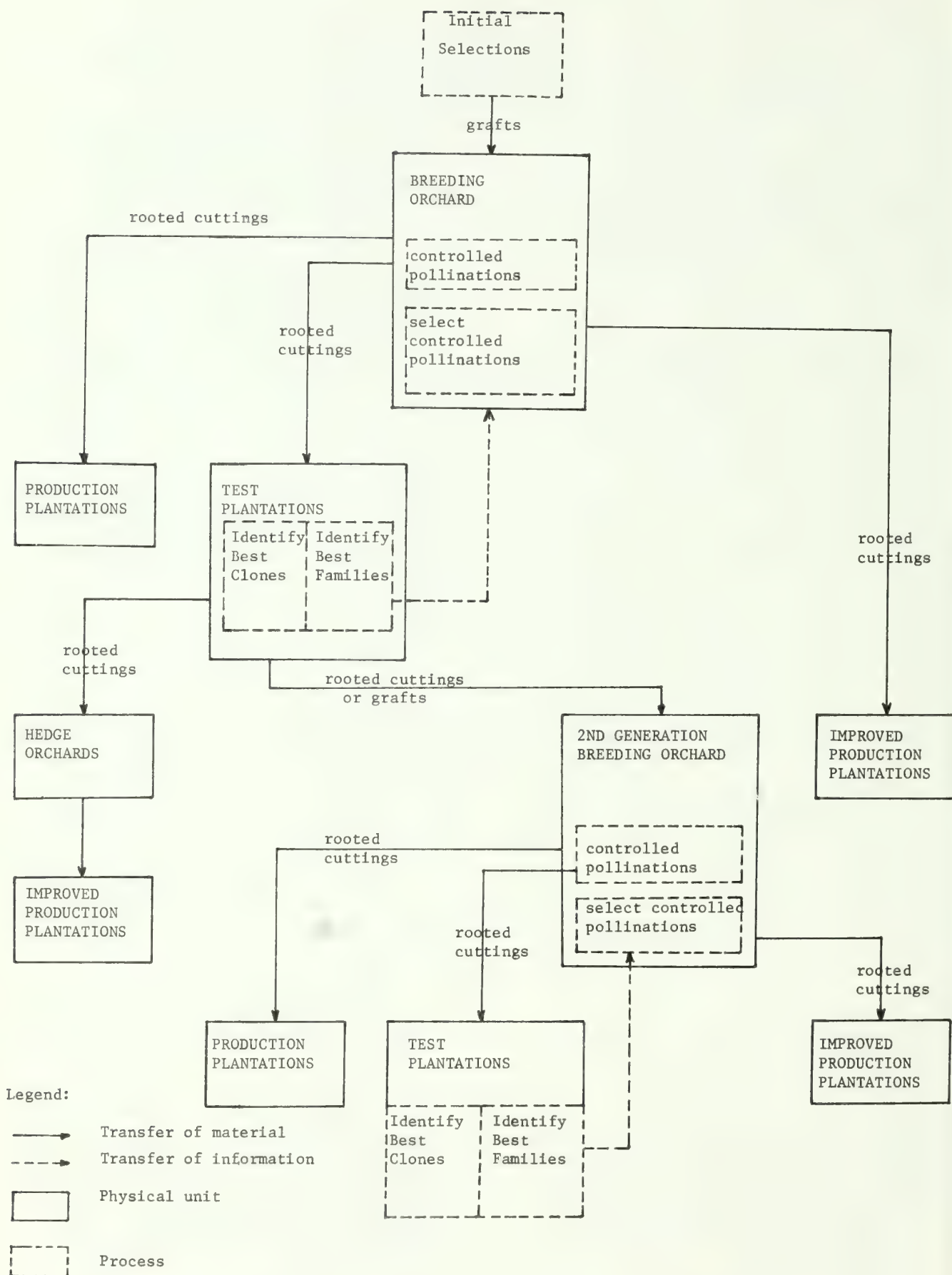


Figure 5: Breeding and Production Strategy for Clonal Forestry (Except Poplar)

summary of the Ontario approach for this species is:

-) Strategy I - The Base Program will be in effect until material is available from the seed orchards;
-) Strategy III - The clonal orchard approach will be followed for white spruce;
-) All first-generation production orchards will be clonal orchards;
-) Programs for all orchards will be under way by 1985;
-) All production and breeding orchards will be established by 1993;
-) By the year 2000, all planting stock (either seedlings or vegetative propagules) will originate from orchard material;
-) Research into ways of overcoming the problems with donor stock will continue in an attempt to make the clonal forestry option more viable.

To fulfil the planting needs for white spruce, a total of 250 hectares of clonal seed orchards are required for 21 different breeding zones. The projected annual production per hectare of orchard is 0.2 million viable seed at 15 years, 0.3 million at 20 years and 0.5 million at 30 years of age. The anticipated volume gain in seedlings produced from orchard seed is approximately 4 percent from a 15-year old orchard, 6 percent from a 20-year old orchard and 14 percent from a 30-year old one. Additional gains will be obtained in stem and crown form.

Several factors affect the profitability of seed orchard programs. Interest rates and real prices are the main determinants for long-rotation species and will outweigh any particular program design. However, the shorter the rotation, the more important is the program design and the less the improvement needed to economically justify the program. Many of the costs in the seed orchard program are fixed. Selection costs and tests costs are constant; only orchard establishment and management costs are variable. Thus, the larger the orchard required to supply the seed needs, the less the genetic improvement required for the program to be financially solvent. If planting and intensive silvicultural management of improved stock are restricted to the best sites, the necessary improvement is easier to attain.

The costs of establishing an 8-hectare seed orchard, associated testing and data evaluation were calculated. These costs were used as a basis for an elementary economic analysis of a seedling seed orchard program for black spruce. A number of points resulting from this analysis are highlighted in Table 1. A sub-table 1a shows the number of seedlings and the area that can be regenerated at different seed utilization rates using all of the seed produced during the life of this orchard. Sub-table 1b shows the reduction in area to be planted with improved stock, having different amounts of genetic gain, in order to maintain a given volume production. Sub-table 1c shows the present value savings or loss calculated at a 7 percent discount rate. The figures in sub-table 1c are derived by subtracting all costs

Table 1. Present Value Calculations for an 8-hectare Black Spruce Production Orchard with a 40-Year Life Span (Total Seed Production = 270.4 M Seed)

Sub-table 1a			Sub-table 1b						Sub-table 1c				
Seed to ratio	Seedlings produced (M)	Area regenerated (@2500 trees) (M ha)	Reduction in areas to be planted to maintain same volume production (ha)						Present value using 7% discount (M\$)				
			Genetic Gain =						Genetic Gain =				
			4%	8%	12%	16%	20%		4%	8%	12%	16%	20%
2:1	135.200	54.080	2080	4006	5794	7459	9013	+0.392	+0.990	+1.547	+2.065	+2.549	
5:1	54.080	21.632	132	1602	2318	2984	3605	-0.040	+0.160	+0.346	+0.518	+0.680	
10:1	27.040	10.816	416	801	1159	1492	1803	-0.147	-0.048	+0.046	+0.132	+0.213	
20:1	13.520	5.408	208	401	579	746	901	-0.201	-0.151	-0.103	-0.061	-0.021	
50:1	5.408	2.163	83	160	232	298	361	-0.233	-0.213	-0.195	-0.178	-0.162	

for establishing a seed orchard program from the savings accrued by planting fewer hectares of plantation. It shows that if 2 seeds are used to produce 1 shippable seedling, the seed orchard program is profitable with a 4 percent genetic gain in volume production, whereas if twenty seeds are used to produce 1 shippable seedling, the program is operated at a loss even if a twenty percent genetic gain were available. Since seed utilization plays such a large role in the profitability of the seed orchard program, it is essential to have good greenhouse and nursery practices.

This financial analysis concentrated on avoiding costs that occurred in re-establishing the forest with unimproved stock. There was no attempt to estimate anticipated benefits from improving the quality of the lumber, fibre, or the reduction in harvesting and milling costs that would result from the improvements. Such analyses are beyond the scope of this document, but if done, would reveal even greater benefits from a properly developed tree improvement program.

Summary Statement

The policy document has been just completed and sent to field foresters and forest geneticists for critical review. Once the comments have been received and incorporated, the policy will be submitted to senior management. If it is approved and satisfactorily funded, Ontario will once more have the opportunity to take the lead in tree improvement in Canada.

INFORMATION NEEDS FOR PEST MANAGEMENT IN AGRICULTURE

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Journal Article 11392.

The use of modern computer technology in pest management has so far not justified its cost. Systems models and on-line pest management systems have not resulted in control beyond the increased efficiency of pesticide applications. Research evaluating entire ecosystem "design" as a variable in pest control reveals that current designs often require pesticide use for stabilization, but that structural modifications can reduce these requirements and provide a new role for computer technology, as yet undefined.

Pest management has placed new demands on information requirements for effective pest control decision making. We must analyze these needs independently from hardware and software limitation. To use modern computer technology for networking to process more efficiently control recommendations as currently practiced does not justify the cost of information system development. In this talk I will briefly trace the history of computer use in IPM at Michigan State University. I will project some alternate potential futures utilizing computer technology to evaluate ecosystem design characteristics.

The development of effective pest management must rely on basic biological knowledge about the pest species and its environment. To this end a great deal of research effort has been expended to quantitatively describe population changes of pest insects. At present, it is clear that the acquisition of detailed biological parameters is not sufficient, even with the aid of models, to bring about effective pest control. This conclusion has not been easy for me to accept even though I have been involved with four major pest research programs, each dedicated to disproving this distasteful conclusion.

First there was the work I was involved within the late fifties and early sixties on the European pine shoot moth. Other forest entomologists (like George Green, Phil Pointing, William E. Miller and Bill Drooze) were all involved in population studies concerning this pest. The economics of the problem diminished but our research did not impact its reduced pest status on pine. The published reports are indirectly useful for management consideration but no definitive management approach was recognized. I thought at the time our resources were too limited and sampling was too ineffective to show the fine differences necessary for detailed parameterization.

During the early sixties, I worked on the spruce budworm in the Green River Project. Neither resources or historical data were limiting factors with this project. During the period of time I was directly involved with the spruce budworm, quantification of population parameters was the specific intended goal of most of the work. Modeling was limited to least square analysis in a search for specific associations. It appears that

this work and much of the work that followed did not lead to spruce budworm control.

By 1966 I had left Fredericton and had become involved with a new pest, the cereal leaf beetle. Many others continued spruce budworm research that ultimately lead to the "Canusa" Project and this meeting in Burlington. From my perspective the cereal leaf beetle project followed a much different route than the spruce budworm program since 1966, but at this point in time may be similar. We have had little or no direct impact on control. Most of you are aware of the spruce budworm research but let me for comparative purposes familiarize you with the approach utilized with the cereal leaf beetle and briefly summarize the intensive research conducted on this pest (see Battenfield et al. 1982).

Field work on the cereal leaf beetle included an extensive survey which measured regional population change, and intensive studies in three locations. The intensive studies utilized a life table approach for both the pest and plant development. By 1970 information was available to undertake regression analysis of individual components. However, it became apparent that the coupling of these models into a more complete model would require more than conventional analytical techniques. Fortunately the project was able to enlist the cooperation of systems engineers in the Dept. of Electrical Engineering at Michigan State University. The engineering concepts of systems and the associated analytical techniques have become an integral part of pest management research in Michigan. Haynes and Gage (1981) summarize the development of component models for the cereal leaf beetle life system in a review article tracing the cereal leaf beetle project's 16-year history. Population models and simulations were developed by Ruesink, Tummala, Lee and Gutierrez. The models of Ruesink and Tummala were based on difference equations but were capable of simulating several generations of the cereal leaf beetle and parasites. Most models, however, were site specific and restricted to within-generation dynamics of the pest. These models were very good and lead to additional insight into the interactions of populations but the resulting simulations did not lead to control. Models associated with dispersal had a similar fate.

Sawyer tested the hypothesis that beetles moved at random between fields. The number of beetles in a field at any particular time was a net result of immigration and emigration rates. The rate on entering a field was a function of the spatial distribution and nature of both overwintering sites and other nearby fields and the relative length of the field's boundary. The rate of departure depended on the suitability of conditions within the field. The spatial distribution of beetles among fields related to general features of the region, such as relative acreages and developmental synchronies of the different host crops.

Currently, three different models are associated with the dispersal of cereal leaf beetle adults through a region: (a) in which the population moves from grass to wheat to oats, (b) in which the population moves to wheat or oats and remains in the field, and (c) Sawyer's model mentioned above. At present it is not known which of these models are correct for cereal leaf beetle movement. Each model can describe observed events but each would lead to different strategies for potential regional cereal leaf beetle management. This fundamental question of how the adult beetles disperse and move between fields has been defined and modeled, but the models have been of no direct use.

A series of simulation models were developed for specific purposes. For example, a model to assess the feasibility of strip spraying for the cereal leaf beetle was developed to simulate a variety of strip configurations, insecticide concentrations, and cereal leaf beetle adult movement rates. A model describing oat growth in the presence of cereal leaf beetle populations was developed to simulate the interaction between oat growth and cereal leaf beetle feeding. This model simulates a single cereal leaf beetle field under different environmental factors, fertilizer treatments, and cereal leaf beetle densities and can be used to screen temporal synchrony between the beetle and the plant.

A quantitative model was developed for improved density estimates of cereal leaf beetle larvae taken in a sweepnet. Fulton developed a model to evaluate the influence of cereal leaf beetle population maturity with respect to developing monitoring techniques. These models were used to estimate seasonal incidence of cereal leaf beetle larvae from a single population density estimate by incorporating weather and developmental rates estimated for cereal leaf beetle larvae. Casagrande and Haynes developed a model to evaluate overwintering mortality of adult beetles exposed to subfreezing temperatures. Sawyer and Haynes used an analytical approach to optimize the allocation of limited sampling resources in order to estimate regional cereal leaf beetle populations.

These models with specific, limited objectives appear to be the most effective, but by themselves do not lead to control. Three different simulation models of the cereal leaf beetle life system have been developed but were also of little direct use in control.

However the availability of this systems model lead to the on-line control paradigm for pest management programs (Haynes et al. 1973). It was felt that if this model could be synchronized with the environment it could be used directly in an on-line interactive manner.

The components of on-line pest management include (a) environmental monitoring, which provides information on weather in relation to biological activity of the life stages of the cereal leaf beetle, its parasitoids, and host plants; (b) biological monitoring, which comprises a regional survey of cereal leaf beetle density and measures the proportion of the population parasitized by each species of parasitoid, the host condition, and the relative proportion of host species; (c) cereal leaf beetle ecosystem modeling, which brings together each of the above components in addition to allowing mathematical experimentation with the system; and (d) a computer-based delivery system, which provides access to the information for remote terminals.

This process has been useful in identifying priorities for cereal leaf beetle research and attempts to implement models. A diagram of the conceptual framework for each component in the system is given in Figure 1. Tummala and Haynes (1977) described the general features of an on-line pest management system.

Many of the biological investigations of the cereal leaf beetle under field conditions indicated that weather played a major role in factors such as cereal leaf beetle adult overwintering survival and emergence from overwintering sites, transition of adult cereal leaf beetle from winter wheat to spring oats, synchrony of larval feeding on different ages of host crops, synchrony of parasitoid attack on cereal leaf beetle larvae and eggs, overwintering parasitoid survival in the soil,

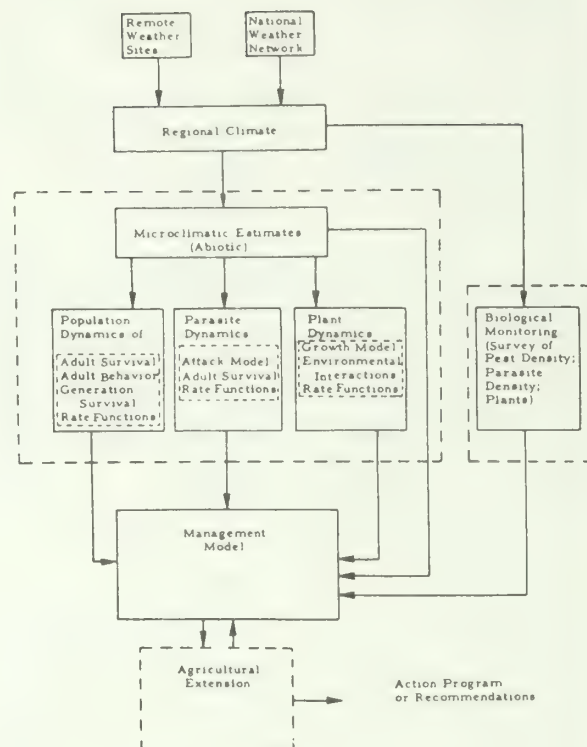


Figure 1. Environmental monitoring network for pest management systems, from Haynes, D. L., Brandenburg, R. K., Fisher, P. D. 1973. Environmental monitoring networks for pest management systems. *Environ. Entomol.* 2:889-899.

and survival of cereal leaf beetle pupae prior to emergence of summer cereal leaf beetle adults. In addition to the effect of weather on cereal leaf beetle and its introduced parasitoids, weather also affects host growth and development. Survival of cereal leaf beetle populations depends on the condition of the host crop, which in turn depends on nutrients and available moisture in the soil. Growth dynamics of small grains can rapidly change during the growing season; therefore modification of conventional economic threshold levels assigned for recommendation of management efforts is necessary.

The regional nature of cereal leaf beetle populations, the necessity of estimating when different life stages of the population occurred within a region, and the variability of weather in Michigan led to an investigation into the needs and kinds of developments necessary for a statewide weather monitoring network. Since current weather data were required to develop the on-line management paradigm, various network configurations were examined, as well as documentation of weather information requirements. These studies not only identified weather needs for cereal leaf beetle decision making but also generalized these needs to include a weather information delivery system for pest management. During the early 1970's, hourly weather data was available, via the Aviation Weather Network, from 14 weather stations located at airports.

To determine the use and applicability of regional weather data, historical weather data were obtained to

assess the value of cereal leaf beetle life stage prediction. A method to correlate real time and historical weather data to increase the usefulness of historical data for on-line pest management was developed. Weather data were used to predict the occurrence of cereal leaf beetle life states in order to accurately determine when to survey (using computer-mapping) for cereal leaf beetle in Michigan. Weather data and computer mapping were used to develop the concept of the "biological window" (Fig. 2).

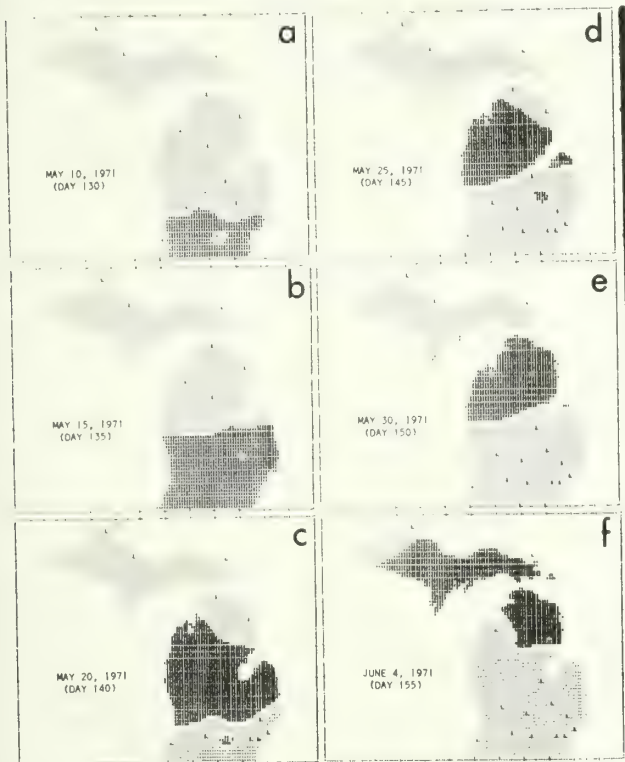


Fig. 2. Illustration of the concept of a biological window where the dark portions (x) indicate regions in Michigan in 1971 where control of adult cereal leaf beetles could be initiated using a short-lived pesticide (e.g., malathion) without killing the parasite *T. julis*.

Although temperature and precipitation data are useful for input into general regional models of cereal leaf beetle occurrence, weather stations located at airports and in other nonagricultural sites did not provide the level of accuracy required for prediction in agricultural sites where cereal leaf beetle populations occur. This problem prompted investigation of cereal leaf beetle microhabitat weather to define the variability of weather between standard weather stations and cereal leaf beetle microhabitat weather. Satellites and other modes of weather data transmission from remote sites were used to determine the optimal location of automated weather stations in Michigan. These and other activities relating weather to pest biology have led to an operational weather delivery system in Michigan. The system consists of 61 weather stations. Information users can access current daily weather for any or each of these weather stations.

Out of the research on the cereal leaf beetle came a regionally oriented pest management program.

This system utilized models, computers and extension personnel in a highly interactive communications system. However, it appears to me (this is not generally accepted) that the principle use of the computer based information system was to accurately and efficiently time the application of pesticides. We had what I eventually came to call a "dynamic spray calendar". How do you control the spruce budworm after 37 years of relatively intensive ecological research?

The question came to mind again, "Is the only solution for pest outbreaks the use of pesticides? Will all detailed studies of pest systems finally revolve around the use of pesticides for control?"

These programs, the European pine shoot moth, the spruce budworm and the cereal leaf beetle, in my opinion were and are all excellent studies. They have not lead to solutions. We have excellent analytical tools, access to very sophisticated computers and adequate if not opulent budgets to conduct this field research; why then is so little progress made toward non-chemical control of pest populations?

In 1976 we initiated a new program where we examined this question in the context of the entire ecosystem. We intended to evaluate ecosystem "design" as a variable in pest control. Successful biological control through the interaction of exotic parasites or predators is a clear example of design modification for control. The design of the ecosystem is the structural components which interact together to produce a particular ecosystem behavior. In more gross engineering jargon it could be said that: the specific objective of the design is to articulate the structural options of the ecosystem under consideration to achieve the desired behavior of the system. For example, introduction or removal of a parasite or predator component from the pest system would be a design change. Management of the ecosystem assumes the structure of the system to be fixed, while certain key parameters like time synchronies between the parasite and the pest, planting dates, fecundities, mortality rates, fertilization levels, etc., are managed to obtain the desired system performance.

When a system is being managed (tuned) to give a desired response, the underlying assumption is that the set of desired behavior (B) is a subset of all the admissible behaviors (A) exhibited by the system under varying conditions; i.e., we assume $B \subseteq A$. If this assumption were not true, then set B does not include the desired behavior. In this case we have to expand the behavioral space by including more components in the system under study.

In most situations the structure of a pest control problem is considered fixed even though it has evolved to its particular state slowly over time. It appears that in many problem areas the current structure requires the use of pesticides for stabilization.

If we view pest control in this light we can conclude that pest management at its best is the incremental adjustment to the current system and does not address the problem of reducing pesticides. It simply removed the pesticides which were not needed but can not address the question of removing pesticides needed with current design. This is extremely important if the current design is unstable over a long time frame. This leads to a whole series of problems which may be answered through research if properly stated. When you have designed a particular system and it brings about pest control, what in that system brought about pest control? If you design another system,

would you have that pest control, or would you lose it? Could the design, and alterations to that design, actually be used as a management variable? Could you design a system that had more control options in it than another system?

To do this, you have to come up with a fairly clear definition of what the systems structure is. What are these things that we're working with? What are the components of this particular system? What structural modifications can be made that would bring about additional control?

In our search for a cropping system to serve as a suitable template for several university disciplines, we looked for a system that was small, manageable, rich in ecological, economic, and social principles, and representative of the energy-intensive agriculture paradox. The onion pest-crop agroecosystem of the Northeast and Lake states offers a near ideal prototype. Onions (as well as celery, lettuce, and carrots) are cropped on remnants of bogs, which were formed when receding glaciers left small pockets of perched water tables. Once drained, they provided unique soils (muck soil) where vegetable crops grow well.

The onion pest-crop agroecosystem is an ecological island because it is a closed system with definite borders (ecological, physical, economic, and social). Muck soils have a unique interface with surrounding mineral soils, so the types of crops grown, their biotic cohorts, and the indigenous ecological communities are distinct from the surrounding landscape. (In fact, the anomaly is so complete that the specialized skills required to grow these crops can be identified with a small ethnic subset of farmers. For instance, in Michigan most muck farming is done by second- and third-generation Dutch farmers, whose forefathers were familiar with intensive agricultural technology from the low countries of western Europe.)

The onion-pest crop ecosystem is also an excellent prototype because:

- The existing system is the result of energy-intensive cropping and chemical control practices.
- The organic soil ecosystem is a relatively simple one, which contains most of the basic interactions inherent in larger, more complex agroecosystems.
- The pests of this system have a long history of pesticide resistance.
- Crop losses due to pestilence range from 10 to 40% of the estimated annual crop value.
- Despite heavy reliance on pesticides to ensure high annual yields, 10-30% of the crop is discarded due to unstable and restrictive markets.
- Amortization of capital investment is slow.
- The crop protection strategy of insurance spraying is threatened with the accelerated premature displacement of pesticides.

Due to the specialized nature of the crop (nonessential for subsistence) coupled with the high cost of pesticide registration and the lack of economic incentives, pesticide companies are reluctant to develop new materials. As a result, this cropping system and many others like it are unstable and have difficulty adapting to changing conditions.

Onion production is intensive agriculture. In Michigan, we've reported more than 51 compounds put on one crop of onions. We're now down to very few chemicals available for even marginal control. Like the house fly, it is resistant to most pesticides.

Figure 3 shows the structural features of the onion ecosystem. We have an object of control and a

monitored environment. In our plan the object of control was to be studied and modeled. The monitored environment were things to be monitored as both controllable and uncontrollable variables (Tummala and Haynes 1977). If something became important, we would include it in our object of control model. There were some very important components we were just monitoring, but within the object of control, everything was quantified and measured from the reference point.

We felt that if we were going to work within an agroecosystem, it had to be tied to some biological component. In this particular case, we tied it into the onion. Everything in the ecosystem, including man's activity, or anything else, we measured as a point of interaction from the onion crop (Figure 3). First order interactions were the pests, the leaf blight, the onion maggot, the onion thrips, and the northern root-knot nematode. Those are four first-order interactions, and that's where pest control specialists have spent all their time attempting to control pests, trying to break that linkage. If you look at the second order interactions, you see that the fungus of the onion plant had a fungus disease that attacks it. The onion maggot has a nematode that attacks it, plus a fungus disease, and series of predators and parasites. You can move on up into the third order interactions, where you find that the parasite attacking the onion maggot also had a fungus disease killing it. So, if we could put up such a structure, where we could look across orders of interactions, and then set up experiments, where we could measure those flow rates, we felt we could perhaps come up with an understanding of what that whole structure looked like.

We did this before we went into the field. We did this by going through the literature back to the turn of the century and finding out everything we could about the relationships that existed in there before we set up the experiment. We also came to the conclusion that when you were looking at this ecosystem, the last place you're going to find those relationships will be in the conventional agricultural setting. Conventional agriculture has been driven by a set of inputs that have changed the ecological relationships that exist there. We're trying to search for ecological relationships that could survive if we modify the structure.

Therefore, the only hope we had was to develop something called a noncommercial ecosystem, where we did not grow the crop for the purpose of producing the crop. We grew the crop to produce potential interactions. We were looking at all orders of interactions. We selected two places. One of them happened to be an organic farm, the other was the MSU property at the Laingsburg Muck Farm, where we actually systematically planted onions and planted weeds and hauled in insects from other areas and tried to make something a farmer would probably call a mess—we called it an ecological soup or a "pristine" situation. Within this context interactions took place. Our intent was to take one interaction at a time and compare it to a commercial agriculture situation. This approach did not lend itself to well-designed statistical experiments. We did not know what was possible and later we concluded that the well-designed field experiment was part of the problem, not an aid to the solution.

One of the experiments looked like this (Figure 4). We utilized a three acre field near Grant, Michigan. One part was a nontreated area and received no pesticides. The other side received just the soil treatment: 10 lbs of Dyfonate® applied at the time of seeding for

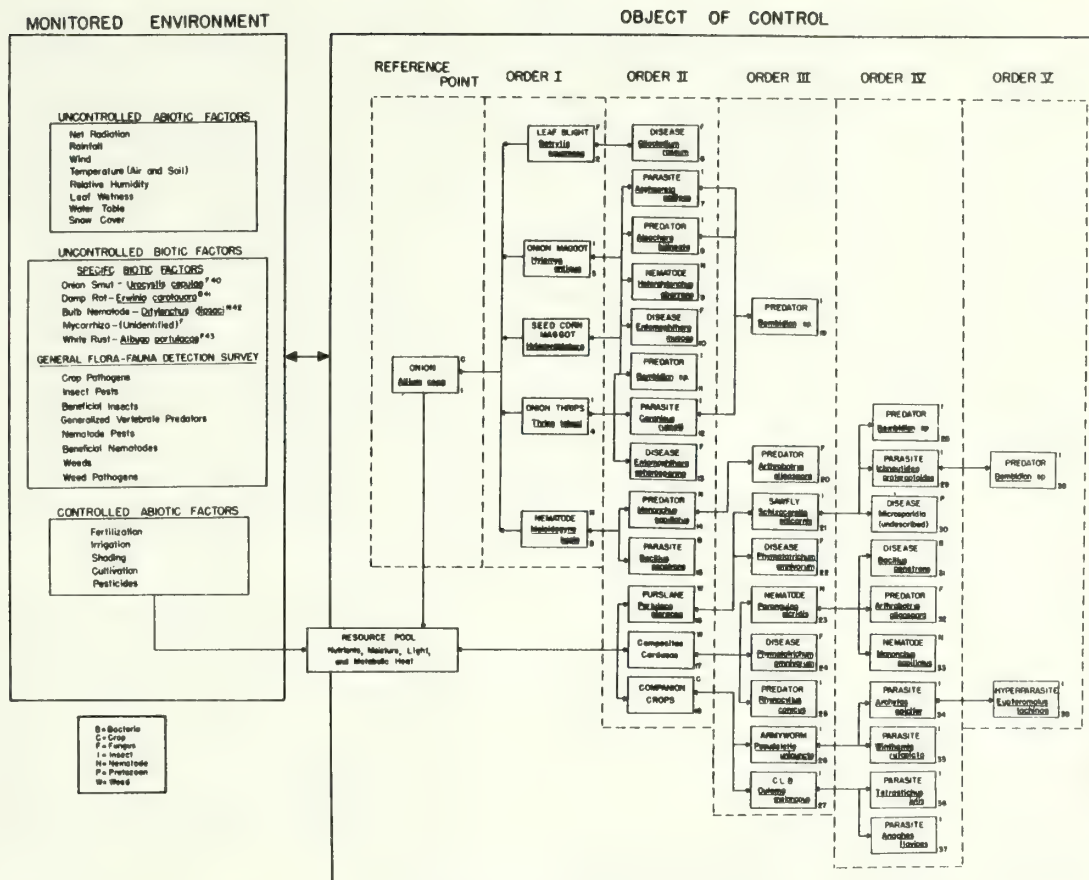


Fig. 3. Structural features showing levels of interaction within an onion agroecosystem design (object of control) and the monitored environment. Letters refer to the role of the organism.

onion maggot control. The surrounding onion field received conventional treatment, which at that time was about 10 lbs of Dyfonate at planting time, and between 12 and 17 foliar sprays for adult onion maggot. This was right in the middle of a commercial growing area. If we look at the place where we only put on Dyfonate, we had a crop with about 2-3% damage. If we look at the surrounding fields, where all the sprays went on, we had a crop that received 2-3% damage. If we look at the place where we took out the pesticides, the crop was totally destroyed, was just wiped out. So clearly we have a good IPM here. We could say, "Look, the foliar sprays are not needed. We don't know how they got in there, but they're doing no good." We followed up the following year with a 10-acre field, one side received Dyfonate and all the foliar treatments, the other side received only Dyfonate. There was no difference. The following year we put in 40 acres and demonstrated a similar thing. The sprays were not necessary. There was no more research needed in this area, although a great deal of extension needs to be done, because five years later farmers still spray.

But that wasn't the research question. If that was where the experiment stopped, we would say that this pesticide, Dyfonate, is absolutely essential or you don't grow onions. However, in the organic farming situation, we had a crop grown after 5 or 6 years of total crop failure. The farmer got to some point where he could grow onions, and there was no Dyfonate there.

Think now for a minute about the implications of alternate design. If we tested a chemical like Dyfonate, as good scientists, up in a commercial growing area, we would say it's absolutely needed—the crop cannot be grown unless you use this pesticide. If at the same time we went out to this organic farm and put out plots with Dyfonate, we would see no economic reason to use it. Now, think about how frightening that idea is—if you are in a particular system, you cannot even run an experiment that will tell you the ultimate truth about what has taken place. In one situation, Dyfonate

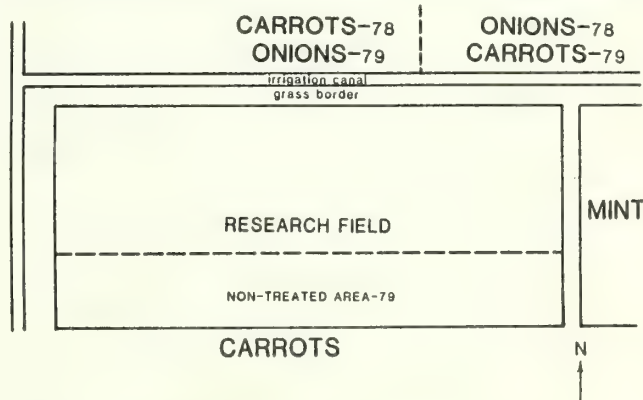


Fig. 4. Plot design of the research field in Grant, Michigan, for 1978-1979.

is needed. You can justify it with all your economic theory, however you want to look at it, and in another system you can justify it not being used. Experimental design and statistical analysis will not provide the truth, only a philosophical comparison of two structurally different systems allow the problem even to become evident. We began to look at why this was true.

One reason was because of cow pats and the face fly. Ellie Groden took bunches of onions that were infested and laid them next to a pasture, where the parasite, *Aphaereta pallipes*, had its alternate host available to it. Near the pasture we got 75% parasitization. Moving away from it, parasitization dropped to zero. When we began to specialize in high-energy inputs, where the cows are pulled away and specialized in one area and onions are grown in another, we ripped apart the life system of this parasite. It no longer had the two components it needed. The only way that could have taken place in the beginning is if you had pesticides to substitute for what this parasite was doing. The pesticides did not have to kill the parasite—we modified the structure and the pesticides were available to take up the lost control component.

We began to look at other pests in the same light. *Entomophthora muscae* is a disease of the onion fly. When we figured out its life cycle, we found that 90% of the disease inoculum that was dropping into the field was dropping in on the edge of the onion field, right at the border. As flies moved from carrots and weeds into the onions, they died and spores from the cadavers were falling down in a narrow band.

When we harvest onions, we spread the cull onions over the entire field and the behavior of the onion maggot changes—it relates to the whole field. But now all the disease is built up back there in the narrow band between those two crops. So we use high energy to spread the distribution of the adult flies that will emerge in the spring, removing them from the whole season's build-up of the disease in the narrow band. Another inadvertent structural modification.

Another one involves the tiger fly. Its immature stage is parasitic on earthworms. For years one of the compounds recommended in the onion system was benomyl, which also controls earthworms.

Another pest, a staphylinid, is parasitic on the onion fly pupae, and the adults are predaceous on the larvae. The staphylinid, however, can't live in a commercial area where herbicides are used, because the soil is black and bare to the sun. Soil temperatures rise up to over 140° and kill it. You would find if you weren't going to use herbicides, you'd have to use

mulch, and then these things would build up and increase in number.

What had happened to this organic farmer who successfully grew onions? He switched from commercial practices for religious reasons after he was knocked down by a chemical. He said, "I will not use any chemical no matter what." And he lost his crop, and he lost his crop and he lost his crop, because God's balance wasn't right. At some point in time, though, something began to happen. If you think for a minute, in terms of accidents, if you're a farmer and you're starving and you can't produce a crop, the first thing you do is get a cow. Even if you can't sell the milk, you have something to eat. If you have a cow, you pasture the cow, and if you pasture a cow, you make long and narrow pastures, which maximize, in scientific terms, the border/field ratios. This would build up the parasite, *A. pallipes*. If you weren't going to use herbicide, you'd have to use an organic mulch and that would build up the system where the staphylinid beetle could live. You would also be building up earthworms, and thus the tiger fly.

These are the kinds of structural modifications that can be experimentally defined in this system. How you go from one system to another economically is still unknown. This grower suffered total loss. There may be transitions from the way we do it now to where we want to go, with various transition costs. Some will be more viable than others.

I think this is an exciting area of research, looking at the structural implications, the population dynamics and pest management. I think a great deal of work in the future will somehow relate to this particular subject.

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INTRODUCTORY REMARKS FOR PANEL DISCUSSION;
MANAGING SPRUCE BUDWORM IN VERMONT

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Because the spruce budworm problem is new to Vermont, Vermont is new to the budworm. Not that the budworm hasn't been around, but for some reason or reasons it remained at relatively low population levels in spite of several periodic mass flights of moths into the northeastern part of the state, until some ten years ago. Having been around a while, I have often wondered why the spruce-fir type in Vermont, apparently resistant to spruce budworm damage for so long, has become so susceptible in the last decade. It seems almost as if spruce-fir forest use patterns had changed enough to alter susceptibility to budworm over a relatively short time. Because of this, the Vermont situation perhaps affords a unique opportunity to look back a few decades and try to determine what we were doing then that we are not doing today or what we weren't doing then that we are doing today that could account for the change in susceptibility.

Considerable public interest in the budworm problem has developed in the Northeast Kingdom not only because of the importance of wood products to the local economy, but also because sizeable deer yards exist throughout the area. Opposition to the use of chemical insecticides has presented a difficult climate for carrying out direct control with anything but B.t.; but this has proved helpful in gaining support for an integrated approach to control through other pest management techniques such as species conversion, planting, encouraging polyculture, shorter rotations and silviculture. We remain hopeful that with what has been learned by others before us, together with some insight gleaned from the recent history of budworm behavior in Vermont, that a truly integrated pest management strategy can be developed, tested and demonstrated which will allow us to manage the budworm on an on-going basis through "comprehensive husbandry based on sound ecological fact and theory". (Geier and Clark, 1960). "Although greater creative effort will be necessary, (this approach) should prove to be less costly, invoke less social and ecological repercussions, and be of more lasting benefit than the continued use of present-day methods which ignore the ecological realities of pest regulation." (Stark, 1970).

To this end, the Vermont Spruce Budworm Management Demonstration Project is dedicated as will be borne out by the various contributors to this panel.

Panel: Managing Spruce Budworm in Vermont

The panel discussions reflected the concerns and issues that shaped the Vermont Spruce Budworm Demonstration Project, a joint effort of the Vermont Department of Forests, Parks, and Recreation, and the Northeastern Area, State and Private Forestry, U.S. Forest Service. We present below the opening statements of the panelists, each of whom represents a constituency with varying but compatible resource management goals. Budworm feeding alters the environment in which normal management processes take place. The nature of the adjustments required are what the panel is about.

Vermont Spruce Budworm Demonstration Project Background

by

Sam T. Hudson, Jr., Project Leader
Vermont Dept. Forest, Parks and Recreation

The spruce budworm is a relatively new forest insect problem here in Vermont, first building up to noticeable levels in 1974.

During the past nine years, the outbreak has increased in size, acres infested - and intensity, damage incurred.

1983 surveys list nearly 180,000 acres of spruce-fir stands currently being damaged in Northern Vermont.

Spruce fir stands which have been repeatedly defoliated are now deteriorating rapidly and new mortality is increasing.

The total timber value of the affected five-county spruce-fir resource exceeds 50 million dollars. The value lost to budworm currently exceeds 2.5 million dollars per year. This value does not account for deer wintering areas and aesthetics. Landowners, foresters and timber operators in the affected area are concerned about the budworm problem and are asking for assistance. Recent research, specifically that sponsored by CANUSA, has made new technology available.

Advanced technology will be applied on the ground in 1984, during the landowner assistance phase, of the Vermont Spruce Budworm Demonstration Project.

The overall goal of the spruce budworm management project is to reduce the susceptibility and vulnerability of spruce-fir to the budworm. Protecting and maintaining critical deerwintering areas is receiving critical attention.

The project's short term objectives are to provide technical information and assistance to woodland owners where heavy budworm damage is impacting timber, wildlife habitat, and aesthetic values. Project objectives are achieved through training, demonstrations and technical assistance

in management, utilization and protection.

These activities will serve as a model for implementing an integrated approach to budworm management. The demonstration project will serve as a practical model, statewide, for achieving diverse management objectives as outlined in the 1984 spruce budworm demonstration project annual work plan.

SPRUCE BUDWORM/DEER WINTER RANGE: A SITUATION STATEMENT

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Abstract

Social and economic contributions of deer herds to the public well being make the perpetuation and improvement of winter deer range an important consideration in forest management planning. Spruce budworm infestations can lead to deterioration of winter deer range quantity and quality. The responses of deer to winter weather, winter deer range characteristics and silvicultural recommendations for managing spruce-fir winter deer range are discussed.

Introduction

The Vermont Fish & Game Department's interest in spruce budworm defoliation is centered upon an anticipated deterioration in quality and acreage of winter deer habitat. We are vitally interested in ways of lessening the damage to winter deer habitat and anxious for the development and implementation of silvicultural practices that will lessen the impact of budworm outbreaks in future years. It is our desire to maintain deer populations at the highest levels range conditions will allow in order to provide satisfactory recreational hunting opportunities. This is what Vermont hunters want from their deer herd. A remnant population may have scientific purpose, but no real social and economic values. That is not of any interest to us or to the people of this state.

Deer hunting in Vermont is a long standing, highly valued tradition. It is also a big business that generates over a million man days of recreation annually, and as a result \$71,716,115 to this state's economy each year (Gilbert, A. H. Personal Communication) (Gilbert, A. H., 1977). Our Department is

financially tied to the deer herd with license and permit fees generated by deer hunting providing 76.1 percent of our operating budget annually. Anything that lessens deer numbers significantly affects hunter satisfaction levels negatively and can result in diminished levels of hunter participation bringing reduced economic benefits to all concerned.

Socially, deer hunting is important to this state. Picture a place where one in five people is a licensed deer hunter! That is regardless of the sex or age of the people in the population and studies show most Vermont hunters are males between their late teens and 60 years old (Gilbert, A. H., 1977). To a significant number of these people biological principles are totally unknown and are not appreciated. Changes in deer numbers, particularly downward changes, are automatically the Department's fault regardless of the cause. Government officials don't look forward to "good natured" grumbling from 20 percent of the population even if the blame can be placed on a worm. They aren't going to buy that in the deer camp anyway.

States and Provinces to the east have faced this particular problem chronologically before Vermont. Their experiences tell us that budworm defoliation frequently leads to a high intensity softwood logging cycle as the forest products industries attempt to minimize their losses, both actual and anticipated. New Hampshire biologists tell us that the three northern counties of that state produced 60 percent of their state's deer kill during the 1960's and now produce less than 30 percent of the annual kill. Much of the decline in kill can be laid to heavy softwood cuts in old, even-aged deer yards that were infested with budworms (Joe Wiley, Personal Communication). Residual softwood stands left after cutting are frequently marginal in terms of cover quality. The few remaining wintering deer are subjected to additional stress when severe weather conditions occur (Karl Strong, Personal Communication).

Concerned? That's not a strong enough word. Paranoid is more appropriate. Even though our turn has come, we don't look forward to adding budworm infested deer winter habitat to our list of problems needing solutions.

Deer Responses to Winter Weather

For background purposes a highlighting of the interactions of deer and winter weather is necessary. In order to inhabit northern United States and Canada, deer have had to develop adaptations, both behavioral and physical, to cope with stressful winter weather. Some of these adaptations are well known and others have only begun to be understood after two decades of sophisticated research. Essentially the problem for deer boils down to survival to spring. Deer must maintain a positive energy balance with their environment. Arrayed against the deer in their struggle are:

1. Cold temperatures that cause high rates of body heat loss. This radiant energy loss is accelerated when windy conditions occur (Moen, 1980).

2. Snow accumulations that cause increased energy loss from day to day deer movements (Mattfeld, 1973). Snow texture and the length of winter can become critical particularly if there is a marked deviation from regional weather norms. Long drawn out winters with late springs can be costly in terms of deer survival and in reduced fawn production rates (Verme, 1977).

3. Low quantity and poor quality winter foods. The well known relationship between deer numbers and winter food supplies is a corner stone in the case for deer population management. Less well known is the reduction in food quality faced by wintering deer. Even the best hardwood browses are poorer energy sources than the green leaves, grasses, herbs, nuts and fruits fed upon at other seasons (Mautz, 1978). Quantities of food are influenced by deer numbers, forest management and snow depths.

4. Disturbance of deer in winter by roaming dogs, snowmobile harassment and man contribute to deer survival problems by accelerating energy drains when deer are forced into preventable flight (Moen, 1982). Movement takes energy.

Deer respond in a variety of ways to offset winter stress.

1. Insulated winter hair coats aid in conserving energy by retarding radiant heat losses. (Moen, 1980), (Silver et al, 1969).

2. Physical activity levels are reduced. Deer are reluctant to run in winter unless pushed. Slower movements cost less. This is important when the expenditures cannot be balanced by income from increased feeding. (Moen, 1976) (Moen, 1978).

3. The deer physiologically shut down in winter. Their basal metabolism is markedly lowered. Engines at idle burn less fuel (Silver et al, 1969).

4. Stored body fats and bone marrow fat reserves are major energy sources for wintering deer. (Mautz, 1978a).

5. Voluntary food intake reductions have been noted and these are often substantial. (Mautz, 1978b). A reduced need for daily food intake at a time when even on the best of winter ranges food quality and plant numbers are low makes good energy conservation sense. Recent research indicates that undisturbed penned deer can live nearly two months with no food intake. Survival rates were good when deer were exposed immediately to quality foods (DeCalesta, et al, 1975). Although wild deer aren't likely to go as long without food as penned animals this is

n important plus in their favor. Clearly, ending deer into winter with good fat reserves from quality summer and fall habitats and having good spring habitat is vital to deer management and has probably propped up the Vermont deer herd for decades (Mautz, 1978b).

6. Seeking protective cover in winter also contributes to deer survival (Ozoga and Gysel, 1972). In snow country, where spruce and fir are king, softwood vegetative protection is essential to wintering deer. Experience shows that regional snowfall norms are strong predictors of the need for softwood protection. Areas with infrequent and limited snowfalls need little if any softwood as a winter deer range component.

Winter Deer Range Characteristics

Softwood provides several benefits for wintering deer. These stands retain solar heat better and radiate less heat at night than open or hardwood sites (Moen, 1980). They have a more stable, temperature regime so deer can reach a liveable equilibrium under softwoods in terms of radiant heat loss (Ozoga, 1968). This can mean days of added life for deer and may make the difference in whether an individual animal sees spring or not.

Softwood canopies function to break up prevailing winds, lessening wind chill (Ozoga, 1968). Tree maturity and hence size enters the picture here. To have strong enough branches to hold snow requires a decent sized tree. Small softwoods with limber branches slough their snow load directly on the ground making good snowshoe share habitat but very poor deer habitat. Ground accumulations of snow under mature softwoods is at least a third less than is found in open cover types. Deer expend less energy in foraging under these conditions. Strong, supporting snow crusts serve the same purpose.

Winter deer ranges are oriented south, west and east in order of preference. Northerly aspects are used infrequently but are known to winter deer under some circumstance. Aspect is important because the amount and duration of solar energy is best in deer ranges that face south. Not only are temperatures higher but snow melt is enhanced.

Usually, winter deer ranges are at low to moderate elevations. Sites below 1500 feet MSL are preferred in Vermont although winter ranges at higher elevations are known to occur. Again, snow accumulation appears to be the principal factor with lower elevations receiving less snowfall.

In the rugged, mountainous terrain of central and southern Vermont steep slopes that have favorable aspects frequently are key winter deer ranges due to the combined affects of slope degree and aspect upon snow accumulation and solar radiation (Dickinson, 1976). This last attribute of winter range (steepness) is not a

factor in spruce-fir areas of Vermont because topographic relief is less pronounced. Under the topographic circumstances found in northeastern Vermont deer winter range relies heavily upon softwood vegetation to minimize snow accumulations.

For several years,, we have been measuring the physical characteristics of winter deer habitat. We have found regional variations that reinforce our beliefs that snow accumulations are a major factor in cover selections by deer. The cold, hard figures do not reflect the dynamic real life situations of winter habitat as well as we would like. It has become obvious to us that solid softwood stands are not necessary for wintering deer and that they may not even be optimal. While heavy to softwood, Vermont deer range is typically "patchy," with inter-connected dense blocks of softwood mixing with hardwood, mixed and even open sites. Within all areas surveyed there are islands of softwood cover with basal areas in excess of 150 square feet and frequently in excess of 200 square feet, and crown closures over 90 percent. These locales, often only a acre or two in size, are connected by lesser softwood densities sometimes down to single trees that allow a flow of deer movement. The denser cover is probably essential in cold, stormy periods but produces no food (Ozoga, 1968), (Ozoga and Gysel, 1972). Food is found in the less dense softwood and mixed sites nearby. A balance between these conditions, while difficult to quantify, exists in all our winter ranges and this needs to be considered in cut plans.

Potential for Softwood Cover Deterioration

What is the potential for cover deterioration in deer range that has spruce budworm problems? We say the possibility of problems is high. Within the spruce budworm demonstration area (Towns of Craftsbury, Eden, Greensboro, Hardwick, Hyde Park, Stannard, Walden, Wheelock, and Wolcott), eight winter ranges were examined for cover characteristics and browse production. A breakdown of softwood trees by species noted on plots (4 inches DBH and larger) shows 45.9 percent are balsam fir with an additional 23.5 percent being red and white spruce. The balance were hemlock (5.2 percent), white cedar (19.2 percent) and white pine (6.2 percent). Larch is considered a hardwood for this purpose. If high tree mortality occurs due to budworm defoliation winter deer shelter quality will be dramatically lessened and in some locales may be eliminated. Assuming New Hampshire's experience is an accurate barometer we face the likelihood of losing large acreages of winter range and reduced deer population sizes in the budworm problem areas.

We have no winter deer range to spare. The physical requirements sought by deer in winter have been discussed. Most wooded lands including most softwood sites are not usable.

They are too high in elevation, too poor in quality or have a bad aspect. Some sites that to the human eye appear adequate are rejected by deer for reasons that to date are unknown (Weber et al., 1983). You cannot will a particular area to be a deer yard no matter how hard you try. If the deer are telling you a site meets their minimum winter requirements by their presence, go with it. In this matter, deer know more than biologists and probably foresters too.

Winter Range Acreage in Demonstration Area

From mapping work to determine acreages used by deer and browse availability data a rough illustration of the carrying capacity of the demonstration area can be developed. Estimates of existing deer populations can then be compared to develop an approximation of the status of deer range in the study site.

Fish and Game Department field locations and boundary mapping of deer winter range has been going on for years. While there may be small areas we have missed, it is not likely that significant "new" acres remain undiscovered. We estimated 13,500 acres of winter range exist in the Demonstration area. Based upon knowledge of deer range we estimate that this winter range acreage serves a larger summer, fall range of 134,400 acres (210 square miles).

Browse studies of 19 winter deer ranges in the North Central physiographic region of which the Demonstration area is a part, revealed an average of 36 pounds of browse per acre (green weight). The "typical" browse species available in Vermont could sustain an average 60 percent utilization rate without loss of plant vigor. (Severinghaus, unpublished data). Multiplication of these figures leaves 22 pounds of usable browse per acre. Assuming a daily intake for the typical deer of 3 pounds of browse per day (Mautz, personal communication) and an average yarding period of 75 days we need 10 acres of winter range per deer in the Demonstration area resulting in a calculated maximum winter deer population of 1350 deer.

Winter Deer Population Estimates

Fall population estimates based upon the mean buck kills for the period 1979-1983 in this area reveal an average population density of 8 deer per square mile. There are an estimated 1685 deer on the 210 square miles of area served by the 13,500 acres of winter range in the fall. Legal hunting kills, illegal and hunt crippling losses can be expected to trim this herd an average 20 percent before the wintering period (337 deer). An additional 100 deer (5 per square mile of winter cover) are likely to die in an average winter in spite of hunt management to causes such as highway accident, domestic dog and wild predator kills, starvation, old age, disease, illegal kills and other miscellaneous difficulties. This means that the over winter

herd that reaches spring will average 1250 animals. These animals will require a minimum 12,500 acres already discussed. On paper we have 1,000 acres extra range, in fact we doubt if our methods are accurate enough to leave only a 7.4 percent slush factor. We feel there is no leeway right now with the existing deer population.

Let us be the first to assure you that a deer herd of 8 animals per square mile is a very modest population. There are those who would say that it is a shabby population and would like it much larger. For example, most hunters view the present deer population size as too small. Anyone who doesn't believe that doesn't live in Vermont or has been asleep for the past 15 years. A 25 percent population increase is not an unreasonable objective and that would only give us 10 deer per square mile and would require 16,800 acres of winter range. That level of population (10) would be considered mediocre in many States.

Spruce-Fir Silviculture in Winter Deer Range

The budworm problems for Vermont's deer herd will have to be faced even if a reduced amount of deer range and smaller herd results for several years. The real goal should be to minimize present conflicts with winter range. Please take a few chances and don't "skin it all off" just because budworm is present. The future forest composition is what we need to consider so that we don't go through another emergency 50 years down the road due to following expediency in the 1980's. The Vermont Fish & Game Department and Department of Forest, Parks and Recreation have developed the following general guidelines for cutting spruce-fir winter deer range under both uneven age and even age management systems.

Management Considerations

Objectives

Commercial timber operations in a deer wintering area can easily destroy good cover. However, some types of cutting scheme are necessary in long-range planning and can provide additional browse supplies. Three main objectives in managing deer winter range are:

1. Preserve and perpetuate shelter conditions over as much of the original wintering area as possible, maintaining maximum deer mobility.
2. Improve adjacent or future softwood shelter through the regeneration or the release of understory softwood trees.
3. Provide high quality, accessible browse.

Silvicultural Systems

Spruce-fir can be managed by either the unevenaged or evenaged management systems. Unevenaged management is the preferred system to meet the above stated objectives, especially when managing ownerships with less than 100 contiguous softwood acres.

Evenaged systems may be a better choice in larger ownerships due to ease of timber sale layout and administration. This system is also frequently necessary in overmature stands.

Guidelines

The following guidelines should be considered when operating in deer wintering areas threatened by spruce budworm:

Unevenaged Management

1. Maintain an average crown closure of 50 to 60 percent.

2. Group selection cuts are preferred over single tree selection as denser pockets of cover remain and more browse is produced in the resultant openings. Openings should be 20 to 40 feet in diameter.

3. Favor longer-lived, more wind-firm, and budworm resistant species such as hemlock, red spruce, cedar, and white pine.

4. Enter the stand during the winter to provide browse in the form of tops and branches and to create trails.

Evenaged Management

1. Develop an age-class distribution based on a predetermined rotation age and cutting cycle. For example, a 210 acre fir stand in a 70 year rotation could have 30 acres regenerated every 10 years. Regenerate spruce-fir using a two or three cut shelterwood system or strip clearcuts.

2. Shelterwood systems are preferred because they are a more reliable regeneration method which also favor spruce over fir.

- a. Under the shelterwood system, the first cut should remove 40 percent of the basal area. Favor budworm resistant species such as red spruce, cedar, hemlock, and pine if present. Cut from below to remove low shade, leaving the larger and more vigorous trees to provide seed. Summer logging is preferred to prepare a seedbed to encourage a higher percentage of spruce regeneration. This preparatory cut should be made during a good seed year. The second cut (release cut) should occur when regeneration has reached a height

of three to four feet, generally within 5 to 10 years. Winter logging is recommended to protect regeneration.

- b. If the risk of windthrow is high, a three cut shelterwood system should be used. Remove 20 percent of basal area at the first cut and another 20 percent at the second cut. Allow 5 to 10 years between cuts.

3. Strip clearcutting is sometimes necessary in decadent stands, especially those susceptible to severe windthrow.

- a. Strips should not exceed 40 feet in width to obtain adequate softwood regeneration. Orientation should be northeast-southwest to provide cool shade and protection from prevailing northwesterly winter winds.

- b. Cut one-half of the stand in alternating strips. Remove residual strips when regeneration is 3 feet tall, generally after 3 to 10 years.

4. In critical deer crossing areas, travel lanes about 200 feet wide, should be left through regenerating stands to maintain continuity of the wintering area. These lanes should be managed as unevenaged for perpetual cover.

Foliage Protection

Application of bacterial or chemical insecticides may be required to protect trees long enough for management to take effect. Heavily defoliated trees may not produce seed and shading of the seedbed will be reduced.

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COMMENTS

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Many residents and non-residents own the spruce-fir resource in Vermont. This landownership pattern complicates the implementing of any overall management plan. How are landowners encouraged to select silvicultural practices and management objectives consistent with the management plan? Should the Department of Forests, Parks and Recreation encourage harvesting and managing spruce-fir if landowners cannot sell their wood? Currently, spruce and balsam fir markets are poor, and the long term outlook is not any better. The Department cannot expect landowners to finance long-term spruce-fir management at an economic loss.

The Department of Forests, Parks and Recreation must monitor silvicultural demonstration sites to determine long-term budworm, growth/regeneration and economic impacts. Only this way can landowners be convinced that long-term management pays off. Currently, we cannot predict how Vermont stands will respond to these silvicultural practices. In Maine, we now think that partial cuts can increase budworm problems and require subsequent insecticide protection.

The Department of Fish and Wildlife's deer habitat improvement program should pay to protect deer yard trees with B.t. This way, all the deer yards needing protection that year may get treated because the Department lifts the economic burden off a few landowners.

My final recommendation is to intensively survey the demonstration area's soils. With a good soil survey, sites could be accurately mapped and good sites could grow valuable hardwoods, while poor sites sustain quality deer wintering areas.

Schmitt, Daniel, ed. Spruce-fir management and spruce budworm; 1984 April 24-26; Burlington, VT. Gen. Tech. Rep. NE-99. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1985. 217 p.

Presents a technical update of the management of spruce-fir forests. Integrated management of eastern spruce budworm is not yet a reality. The ecological, social, and economic knowledge needed to develop an integrated management system is not available. The conference was designed to move individuals to a higher level of spruce budworm management in the eastern spruce-fir forests.

Headquarters of the Northeastern Forest Experiment Station are in Broomall, Pa. Field laboratories are maintained at:

- Amherst, Massachusetts, in cooperation with the University of Massachusetts.
 - Berea, Kentucky, in cooperation with Berea College.
 - Burlington, Vermont, in cooperation with the University of Vermont.
 - Delaware, Ohio.
 - Durham, New Hampshire, in cooperation with the University of New Hampshire.
 - Hamden, Connecticut, in cooperation with Yale University.
 - Morgantown, West Virginia, in cooperation with West Virginia University, Morgantown.
 - Orono, Maine, in cooperation with the University of Maine, Orono.
 - Parsons, West Virginia.
 - Princeton, West Virginia.
 - Syracuse, New York, in cooperation with the State University of New York College of Environmental Sciences and Forestry at Syracuse University, Syracuse.
 - University Park, Pennsylvania, in cooperation with the Pennsylvania State University.
 - Warren, Pennsylvania.
-



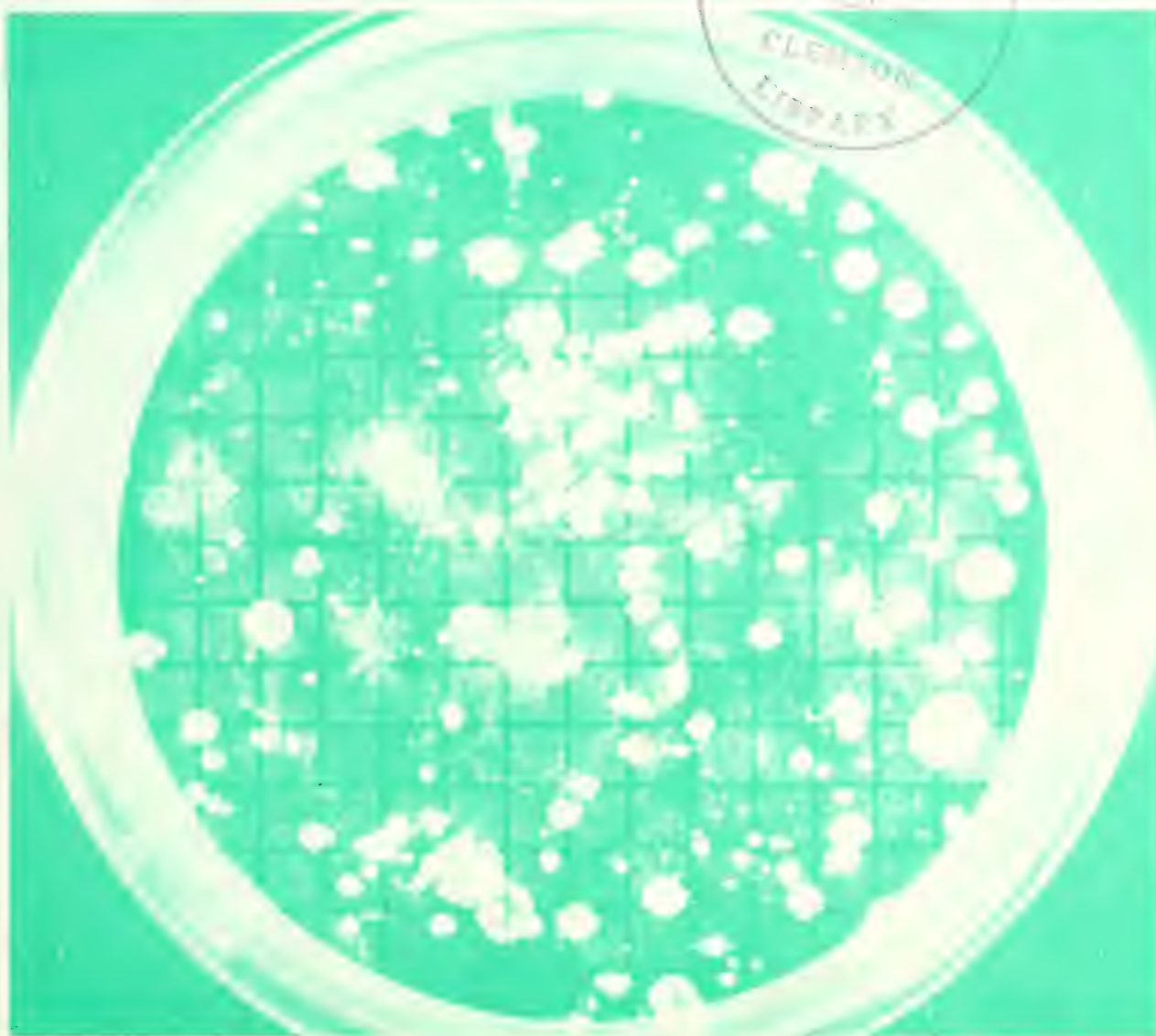
Canada
United States
Spruce Budworms
Program

Forest Service
U.S. Dept. of Agriculture
Northeastern Forest
Experiment Station
Broomall, PA 19008

GTR-NE-100
1985

Proceedings

Symposium: Microbial control of of spruce budworms and gypsy moths



PREFACE

The Canada-United States Spruce Budworms R&D Program (CANUSA) was created in 1977, when the United States Department of Agriculture and the Canadian Department of Environment agreed to cooperate in an expanded and accelerated research and development effort. CANUSA was aimed specifically at the spruce budworm in the east and western spruce budworm in the west. The broad objective was to design and evaluate tactics and strategies for not only controlling budworms but also managing budworm infested forests, thus helping forest managers attain their objectives in an economically and environmentally acceptable manner.

The spruce budworm and the gypsy moth are the two most damaging insects to ever infest North American forests. Both are now, and have been for several years, in outbreak status, with no good hope for relief in sight. Each of them has been the target for millions of acres of aerial insecticide sprays and, since most of the insecticides used have been chemicals, there has been increasing opposition to the programs from groups concerned for the environment.

CANUSA and the Northeastern Forest Experiment Station have supported much research and development work on microbial sprays to suppress high populations of these two insects. State and Provincial land managers on both sides of the border are showing increased interest, and acceptance of microbial agents as a substitute for, or as a supplement to, chemical sprays. Bacillus thuringiensis (B.t.) and, to a lesser extent virus (for gypsy moth), are currently the only registered microbial insecticides available for use by the forest pest manager. Great improvements have been made in the technology for each of these two microbials in the past five years and further strides are expected in the near future. The use of microbial sprays in forest pest control will increase as opposition to chemicals becomes more intense and performance of the microbials further increases. Land owners realize that intelligent forest management must involve protection of their investment in the resource, which under insect outbreak conditions translates into direct control with aerial sprays.

The goal of the symposium was to present state-of-the art information on the development and use of microbials insecticides to pest control officials, researchers and university personnel. This was one of a series of workshops and symposia organized as part of the technology transfer effort of the CANUSA Program. We hope the information contained in the following papers will be of interest and use to forest protection people and forest managers everywhere.

DAVID G. GRIMBLE
FRANKLIN B. LEWIS

Co-Chairmen and Symposium Coordinators

PROCEEDINGS

SYMPOSIUM: MICROBIAL CONTROL OF SPRUCE BUDWORMS AND GYPSY MOTHS

Sponsored by:

CANADA-UNITED STATES SPRUCE BUDWORMS R&D PROGRAM
NORTHEASTERN FOREST EXPERIMENT STATION, USDA FOREST SERVICE

April 10 - 12, 1984
Windsor Locks, CT

Each contributor submitted camera copy and is responsible for the accuracy and style of his or her paper. The statements of contributors from outside the U.S. Department of Agriculture may not necessarily reflect the policy of the Department.

PROGRAM

Tuesday, April 10, 1984

OPENING Remarks: Denver P. Burns, Director, Northeastern Forest Experiment Station, USDA Forest Service, Broomall, PA

Purpose of Symposium: F. B. Lewis, Northeastern Forest Experiment Station, USDA Forest Service, Hamden, CT

USER'S EXPERIENCES - GOOD AND BAD

SPRUCE BUDWORMS

CANADIAN USER PERSPECTIVES ON Bt USE for PROTECTION AGAINST SPRUCE BUDWORMS.

H. J. Irving, Managing Director, Forest Protection Ltd., Fredericton, N.B.

OPERATIONAL EXPERIENCES with Bt in the Eastern United States.

Henry Trial, Jr., Director of Survey and Assessment, Old Town, ME

Four engine aircraft experience in the application of Bacillus thuringiensis against the spruce budworm in Quebec.

Louis Dorais, Quebec Spray Program Coordinator, Quebec

Review of foliage protection spray operations against the spruce budworm with Bacillus thuringiensis Kurstakii from 1980 to 1983 in Nova Scotia and New Brunswick, Canada.

E. G. Kettela, Forestry Officer, Maritimes Forest Research Centre, Fredericton, N.B.

Comparison of Bt formulations against the spruce budworm.

Lew McCreery, Imants Millers and Dennis Souto, Forest Pest Management, USDA Forest Service, Durham, NH; and Bruce Francis, Director of Forestry, Passamaquoddy Indian Forestry Department, Princeton, ME

GYPSY MOTHS

Pennsylvania's experiences with microbial control of the gypsy moth.

James O. Nichols, Chief, Division of Forest Pest Management, Pennsylvania Bureau of Forestry, Middletown, PA

Microbial control of the gypsy moth in recently infested states: Experiences and Expectations.

Timothy C. Tigner, Virginia Division of Forestry, Charlottesville, VA

Some negative aspects of using Bacillus thuringiensis Berliner in operational programs against the gypsy moth (Lepidoptera: Lymantriidae).

John D. Kegg, Chief, Bureau of Entomology, New Jersey Department of Agriculture, Trenton, N.J.

Overall aspects of B.t. in forest service cooperative gypsy moth suppression projects.

Noel F. Schneeberger, Forest Pest Management, USDA Forest Service, Morgantown, WV

RECENT FIELD RESEARCH EXPERIENCE

Spruce Budworms

Recent field experiences with Bacillus thuringiensis in Canada and research needs.

Oswald N. Morris, Agriculture Canada Research Station, Winnipeg, Manitoba

Recent field research experiences with Bt against spruce budworm in the eastern U.S.

John B. Dimond, Professor of Forest Entomology, University of Maine, Orono, ME

Field tests with a highly concentrated Bacillus thuringiensis formula against spruce budworm, Choristoneura fumiferana (Clem.) (Lepidoptera: Tortricidae).

W. A. Smirnoff, Laurentian Forest Research Centre, Sainte-Foy, Quebec

Status of viruses as biological agents for spruce budworms.

J. C. Cunningham, Forest Pest Management Institute, Canadian Forestry Service, Sault Ste. Marie, Ont.

Erynia radicans potential mycoinsecticide for spruce budworm control.

Richard S. Soper, ARS Insect Pathology Research Unit, USDA.

The effect of Erynia radicans on food consumption, utilization and fecundity by the spruce budworm, Choristoneura fumiferana.

Abdul K. A. Mohamed, Lucius Lewis and Denise Lewis, Biology Department, Jackson State University, Jackson, MS

GYPSY MOTHS

Recent field studies on the use of Bacillus thuringiensis to control the gypsy moth (Lymantria dispar L.).

Normand D. Dubois, Northeastern Forest Experiment Station, USDA Forest Service, Hamden, CT

Interactions between microbial agents and gypsy moth parasitoids.

Ronald M. Weseloh, Connecticut Agricultural Experiment Station, New Haven, CT

Gypcheck^r: Past and future strategies for use.

J. D. Podgwaite, Northeastern Forest Experiment Station, USDA Forest Service, Hamden, CT

Recent field research using microbial insecticides against gypsy moth.

Lawrence P. Abrahamson and Donald A. Eggen, State University of New York, Syracuse, NY

Wednesday, April 11, 1984

New Research Developments (What more is needed)

Selection of new more potent strains of Bacillus thuringiensis for use against gypsy moth and spruce budworm.

Normand R. Dubois, Northeastern Forest Experiment Station, USDA Forest Service, Hamden, CT

Chitinase producing B.t. strains.

Haim B. Gunner, Matthew Zimet and Sarah Berger, Department of Environmental Sciences, University of Massachusetts, Amherst, MA

The biochemistry of the protein crystal toxin of Bacillus thuringiensis.

Paul G. Fast, Forest Pest Management Institute, Canadian Forestry Service, Sault Ste. Marie, Ont.

Selection of active strains of the gypsy moth nucleopolyhedrosis virus.

M. Shapiro and E. Dougherty, Agricultural Research Service, Otis, MA

Pathways of nucleopolyhedrosis virus infection on the gypsy moth, Lymantria dispar.

K. S. Shields, Northeastern Forest Experiment Station, USDA Forest Service, Hamden, CT

Enzyme immunoassays for detection of gypsy moth nucleopolyhedrosis virus.

Michael Ma, Department of Entomology, University of Maryland, College Park, MD

Genetic engineering of microbial pesticides.

Bruce C. Carlton, Professor of Molecular and Population Genetics, University of Georgia, Athens, GA

New Developments in Commercially Produced Microbials

Recent developments (1980-1983) in the application of Bacillus thuringiensis for forest insect control.

Robert J. Cibulsky, Abbott Laboratories¹

Developments on commercially produced microbials at Biochem Products.

John Lublinkhof and Douglas H. Ross, Biochem Products, Montchanin, DE

Commercial production of microbials by Reuter Laboratories, Inc., for control of the gypsy moth and the spruce budworm.

F. D. Obenchain, Reuter Laboratories, Gainesville, VA

Recent developments in the Zoecon Corporation and the thuricide^r forestry formulations.

William R. Beck, Zoecon Corporation, State College, PA

DISCUSSION PANEL - FORMULATION AND APPLICATION OF MICROBIALS FOR SBW AND GM CONTROL

Co-Chairmen: Jack A. Armstrong, Canadian Forestry Service, Ottawa, Ontario

William G. Yendol, Professor, Pesticide Research Laboratory,
The Pennsylvania State University, University Park, PA

Panel Speakers: Bruce McGauley, Supervisor Pest Control Section, Ontario Ministry of
Natural Resources, Maple, Ontario

Chester M. Himel, Professor, Entomology Department, University of
Georgia, Athens, GA

David B. Smith, Professor, Agricultural and Biological Engineering
Department, Mississippi State University, Mississippi State, MS

Michel Pelletier, f. eng., Quebec-Energy and Resources Department,
Entomology and Pathology Service, Quebec, Quebec

Paul G. Fast, Forest Pest Management Institute, Canadian Forestry
Service, Sault Ste. Marie, Ontario

John W. Barry, Program Manager of U.S.D.A. Forest Service, U.S. Army
Cooperative R&D Program, Davis, CA

THURSDAY, APRIL 12, 1984

DISCUSSION PANEL - FIELD TEST DESIGN AND DATA ANALYSIS

Chairman: Daniel M. Schmitt, Program Manager, Canusa/US Spruce Budworms Program,
USDA Forest Service, Broomall, PA

Panel Speakers: William E. Waters, Professor of Entomology and Forestry, University of
California at Berkeley, Berkeley, CA

B. Leo Cadogan, Forest Pest Management Institute, Canadian Forestry
Service, Sault Ste. Marie, Ontario

Gerald S. Walton, Northeastern Forest Experiment Station, USDA
Forest Service, Hamden, CT

Coffee

DISCUSSION PANEL - STANDARDIZATION OF BIOASSAYS AND POTENCY DETERMINATIONS

Chairman: Howard T. Dulmage, Insect Pathology Research Unit, USDA,
Brownsville, TX

Panel Speakers: Clayton C. Beegle, Insect Pathology Research Unit, USDA,
Brownsville, TX

Norman R. Dubois, Northeastern Forest Experiment Station, USDA
Forest Service, Hamden, CT

W. A. Smirnoff, Laurentian Forest Experiment Station,
St-Foy, Quebec

SYMPOSIUM WRAP-UP

Peter W. Orr, Staff Director, Forest Pest Management, USDA Forest Service, Broomall, PA

Frank B. Lewis, Northeastern Forest Experiment Station, USDA Forest Service, Hamden, CT

¹No written paper submitted.

Opening Remarks

Thank you, Dave (Grimble). Let me begin by saying that it is particularly fitting that this group meet at this point in time. First, it a fair guess that in the 1984 field season more forest acreage will be treated with microbial insecticides than in any previous year. Second, the research effort devoted to all phases of microbial insecticide formulation and application appear to have arrived at a unique stage when recent R&D is finding ready application -- I am thinking of B.t. -- current R&D, particularly on viruses, fungi, and parasites, is well along in development, and the possibility of genetically tailored biological insecticides is far more than a gleam in a microbiologist's eye. Momentum -- and that's what this group has -- incites achievement.

I also note with satisfaction that our private sector colleagues have a prominent place on the program. Their contributions and viewpoints, both formal and informal, in exchanges with other scientists provide a sense of "wholeness" to the meeting which reflects the informal network binding this group together.

In the same vein I also want to welcome our Canadian colleagues -- many of whom played key roles in the CANUSA program, and those scientists from distant states. Indeed, the geographic diversity of the group and its scientific composition -- engineers, physicists, chemists, and an array of biological expertise -- demonstrate how clearly effective interdisciplinary R&D can be when mutual respect and common goals guide the enterprise.

Another interesting feature of this Symposium is that it brings together experience and expertise on two major forest defoliators, budworm and gypsy moth. The Northeastern Station, while continuing its budworm effort after the CANUSA Program ends in the U. S., will be increasing its level of gypsy moth R&D. Consequently the Microbial Symposium will be of special interest to some of our scientists, and I am happy to say the Station will be publishing and distributing the Proceedings.

In brief I am looking forward to the deliberations of this meeting, so let's get on with it. Thank you.

SYMPOSIUM ON MICROBIAL CONTROL OF SPRUCE BUDWORM
AND GYPSY MOTH

PURPOSE OF SYMPOSIUM

F. B. Lewis

Project Leader, Center for Biological Control of
Forest Insects and Diseases, Northeastern Forest
Experiment Station, Hamden, CT 06514.

The principal purpose of this Symposium is to take advantage of the CANUSA experience, which has engaged so many of us recently, to share and place in the context of our total experience, the current situation regarding microbial insecticides and their use. The exercise will be useful not only for information exchange -- the traditional purpose of symposia -- but also to sharpen and hone future research program planning for microbial insecticide research.

There are many similarities with the microbial component of the 1974-78 gypsy moth R. D. A. Program. Thus the combining of the two in this symposium, many here participated in that effort. Indeed in microbial R & D there are many common goals and problems, regardless of the target insect.

We hope the program - admittedly full packed - will stimulate discussions, friendly disagreements, and at the conclusion a clearer idea of where we stand, what has been done, what remains to be done, and the approaches to be taken. Hopefully a continuation of scientist to scientist interaction we have observed recently will be stimulated and the importance of the problems remaining will be underscored for the administrators present. We certainly hope the International cooperation fostered during the CANUSA program will serve as a model and that this conference will facilitate even more and better cooperation.

A section of this conference will present new research, where it is going, and how it should benefit microbial implementation against these two major insect pests. We will be hearing from the Industrial people and where they see their products and thrust are going. And most

importantly we will be hearing from the users - those on the firing line - and how they assess microbials in meeting their problems.

Our workshop sessions will be slightly different than most and hopefully will capture all the various points of view. They are designed to stimulate open discussion. These workshops will be recorded "in toto" so that the Chairperson will have all statements, comments, opinions in hand to prepare a thorough exposition of the topic area and not miss the casual, but important comment from the floor.

We hope to have the Proceedings of this conference in your hands within a short time. This will depend upon the speakers and workshop chairpersons having their camera-ready copy in quickly if they are not already turned in.

Have a good meeting. We hope you find it enlightening, stimulating and valuable to your sphere of interest.

CANADIAN USER PERSPECTIVES ON BT USE FOR

PROTECTION AGAINST SPRUCE BUDWORM

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Abstract

Reference is made to a recent inter-provincial review of the performance of present-day B.t. viz a viz conventional chemicals. The argument is presented that in the Canadian context its practical acceptability to resource managers remains highly jurisdictionally-specific for reasons over and above conventional technical assessments. The New Brunswick situation is reviewed as a case in point.

I want to say at the outset that the invitation to take part in this symposium was received with pleasure and surprise. Surprise because I believe this is the first or at best the second unsolicited opportunity ever extended to the New Brunswick B.t. user community to say something on its own behalf about the B.t. issue. The closest exception, in Boston a year ago, was also welcomed but was not the open forum that this one is.

I was pleased because it comes at a juncture in the evolution of attitudes and practice in budworm control when generalization about such questions as the viability of B.t. as an alternative to conventional insecticides is no longer enough. I confess to be a bit sensitive about this because in the past year or two it has been driven home to me very forcibly that New Brunswick's performance with B.t. and its alleged attitude toward it is not held in much esteem in some circles. I can agree that there is some justification for this by comparison with the record of our neighbors in Quebec, Maine and, indeed, Nova Scotia. But what I find particularly disturbing and what needs to be challenged is the accusation that this reflects an ignoble pro-chemical, anti-biological mindset that stubbornly ignores superior wisdom elsewhere. To believe that is to ignore a long record of at least decent, self-propelled attention to the question and to reveal a lack of appreciation of the most compelling reasons that ultimately come into play in the performance of individual jurisdictions.

What I was asked to address here, as the program states, are good and bad B.t. experiences in the eastern Canadian scene. My first intention was to approach this in a way that would underscore the point that judgments of good or bad, acceptability or unacceptability cannot

be generalized in the Canadian context, or indeed across international boundaries. Outside experience can be an invaluable guide and technically-qualified advice absolutely imperative. But ultimate responsibility for choices of action or inaction as the case may be are the responsibility of the individual jurisdictions because it is there that accountability lies. Without pointing the finger more in one direction than the other Canadian forestry has historically experienced some difficulty with this distinction at both federal and provincial levels.

With these convictions in mind I had decided to attempt here a synopsis of the good and bad B.t. experiences in the four Canadian jurisdictions judged by the forest managers of those jurisdictions, but without editorial comment. As luck would have it I have been spared that job by the timely issuance of the proceedings of an invitational B.t. seminar organized by my New Brunswick colleague, Rod Carrow, last September. For those who have not received copies it contains assessments of B.t. user experience over the past three years in Ontario, Quebec, New Brunswick, Nova Scotia and Maine. The assessments are made on the basis of four criteria: efficacy, cost, operational peculiarities, and environmental status. This was the first such forest manager-oriented seminar to be held on B.t. in Canada and I particularly commend to you the summary provided by Dr. Carrow on pp.85-90. Capsulized, it says the following.

- (1) Cost remains the major obstacle to greater use.
- (2) There is promise of continuing decline in the cost of the product.
- (3) Application, and therefore over-all costs cannot be presented in a way that permits valid comparisons between jurisdictions. Relative cost of B.t. vs chemical use by jurisdiction provides a more meaningful statistic.
- (4) Recent product and application developments appear to be producing better and more consistent protection, particularly the use of higher BIU rates.
- (5) Certain inherent characteristics of B.t. ensure more difficult application problems.
- (6) The narrower timing window is a fact of life.
- (7) The faith of B.t. developers and users in its greater environmental safety is given insufficient and inconsistent recognition in regulatory circles.

From this applicator's position there is absolutely nothing to disagree with in this assessment. But where Dr. Carrow and I might part company would be in the validity of one of the stated objectives of his seminar, namely "to develop a consensus on the potential for expanded use of B.t. against spruce budworm". In my

opinion, as long as significant advantages to chemical usage remain, until B.t. usage becomes legislated, and while outbreaks continue to exist on their current scale, such consensus is an unrealistic expectation. What must be realized by the more technically-oriented community of B.t. promoters is that the four areas of concern addressed in Dr. Carrow's seminar, which are those also conventionally addressed in generalized reviews by the Canadian Forestry Service and CANUSA do not constitute all of the necessary ingredients of the decision making process in any jurisdiction. It is those extra, highly jurisdictionally-specific factors that defy the development of the jurisdictionally-transferable models of B.t. or chemical usage that some managerially-detached opinion seems to envisage. Perhaps the following table will illustrate the point.

Perspective on Protection Need and Action
Eastern Canada 1983

	Ont.	Quebec	N.B.	N.S.
M-S Infestations M/ha	9000	21000	5300	600
Assessed need extensive protection	Minimal	High	Maximal	Mounting
Sprayed M/ha	3	1254	1495	21
% Infestation Sprayed	0.04	6	28	3.5
B.t. Usage M/ha	3	46	10	21
% B.t. Usage	87	4	0.7	100

It might also clarify the managerial perspective, and correct some misconceptions as well, to examine the New Brunswick story as a case history.

When I took over the management of Forest Protection Limited nine years ago I took over a spraying program already designed and ready to go. It was the largest, most complicated and most costly program attempted up to that time - 2.7 million hectares at a cost of 8.5 million dollars. It had also, as I came to learn, been designed under the tightest budgetary constraints of any previous program. One way of stretching the dollars was to resort to lower dosages. It was a gamble taken in the worst possible year. As some of you will recall, and as the literature testifies, 1975 proved to be a year of such exceptionally virulent budworm activity that exceptionally poor spray results were experienced not only throughout New Brunswick but in Quebec and Maine as well. The results were reminiscent of an earlier cost-cutting experiment in 1956; each case had to be followed by the largest programs ever undertaken up to that time, and in the case of 1976 probably the largest program

ever. At \$15.9 million for 3.9 million hectares it was an experience that has left both government and industrial sponsors very distrustful of chancy and unproven tactics.

As it happens one of the five insecticides used in 1975 was B.t. at a single application of 8 BIUs on 1500 acres. It was an independent initiative of my predecessor who was eager to get B.t. experimentation underway in New Brunswick as well as Quebec. Forest Protection Limited had helped Dr. Smirnoff organize some of his first field trials three or four years previously and had volunteered to substitute B.t. on the watershed of the City of Saint John's water supply. It was turned down, incidentally, because of public apprehension about "germs".

As reported by Ed Kettela at the 1976 Abbott symposium the 1975 trial produced better results than a single chemical application and only slightly less protection than a double. Although I had had nothing to do with the venture I soon became aware that B.t. could be a very touchy subject. The Abbott proceedings also record the late Dr. J.J. Fettes' opinion that such ad hockery was scientific mockery and that such user initiative represented dissipation of effort. Perhaps that is why that result has yet to appear on any CFS score card of "positive" results.

But more important to the case history is that that was the one and only decision taken for or against operational B.t. use by the manager of Forest Protection Limited. To understand the implications of this it is necessary to realize that Forest Protection Limited is a government-industry consortium with the sole purpose of conducting spruce budworm spraying on behalf of its sponsors. Shares in the corporation are owned 90% by the province, 10% by industry. Representation on the Board of Directors to which I am responsible is preponderantly Department of Natural Resources. Until the Department of Natural Resources took over responsibility for biological surveys and assessments in 1983 company decisions relied upon estimates and advice provided by the Canadian Forestry Service through the Maritimes Forest Research Centre. Whatever opinion I, as Managing Director of Forest Protection Limited have had about the viability of B.t. usage in New Brunswick has closely reflected that advice. Under the new Crown Lands and Forests Act industry decides upon and pays for protection on its freehold land; the Department of Natural Resources is responsible for Crown lands and small private ownerships.

As I have said, the evident inadequacy of spraying in 1975 greatly alarmed its sponsors. One major industrial sponsor stated publicly that the formulations used in that year "were no more effective than dishwasher". This, combined with the revelation of the Reye's Syndrome hypothesis pushed budworm management onto the floor of the provincial legislature with demands that the government ensure sufficient research and development to resolve the problem. It commissioned Dr. Gordon Baskerville to advise on budworm control alternatives and a substantial

research and development budget was erected from federal/provincial shared-cost funds. My Board of Directors authorized a Forest Protection Limited research and development budget of up to 3% of total spray budgets.

The way in which this funding came to be applied reflected in large part Dr. Baskerville's advice that the only foreseeable alternatives to conventional protection practice were B.t. and pheromones and that the best pay-back for immediate research and development investment would be in improved technology for conventional practice. Forest Protection Limited then pressed ahead with already-existing endeavors to develop a provincially-based interest and competence in spray delivery technology which has included B.t. usage. The Department of Natural Resources directed some funding to CFS research on budworm dispersal and modelling and deliberated how resources should be directed toward the B.t. and pheromone areas. The decision came down in favor of pheromones. Influenced somewhat by the puzzling antipathy toward user initiative in B.t. trials exposed at the Abbott symposium, and a great deal by the heroic B.t. investments being made by Quebec, it was reasoned that the wiser course would be to concentrate our province's support on pheromone R&D. That recommendation was accepted but in retrospect we realize that it was politically and otherwise not the best. It has been misinterpreted as a lack of faith in B.t. without earning much appreciation for some heavy investments in the pheromone alternative. On the B.t. scorecard, by all means score that episode as a New Brunswick mistake.

So much for that regret, how else does the New Brunswick B.t. record stack up? If numbers mean anything we have sprayed a few more hectares than Ontario, about one quarter as many as Nova Scotia and a pittance compared to Quebec. We have attempted to protect more private woodlots than the others and have severely tested B.t.'s suitability for very sick trees in the process. In more healthy and less difficult targetting situations I believe our record for success or failure by CANUSA standards is not that much different from equivalent experience elsewhere. The tentative indication at this point is that B.t. performed as well or better than fenitrothion for woodlot protection last year. This is encouraging in one way but cold comfort in another, because neither result was that good. As for attitude, this applicator for one has not doubted for some time that given a break with some highly unpredictable and uncontrollable variables, the right application technology and enough money, B.t. could give decent protection. That seemed evident enough in 1975 and from what could be observed elsewhere. We have not been entirely derelict in testing its usability for our needs, witness our efforts in 1979, 1980, 1982 and 1983. But we have been equivocal about spending money in the same old way again and again with no likelihood that we would be the wiser whatever the result. We have not been unwilling to pull our weight in R&D that we could believe in, witness our activity in delivery technology and in shared-cost fundamental research with CANUSA and the CFS.

So what's the problem? As I have already stated it comes back to some totally non-scientific facts of managerial life. It is much easier to accept a greater risk of failure, a higher per hectare cost, and be environmentally noble under an Ontario model than a New Brunswick one. There is no problem accepting limited forest protection with B.t. in Nova Scotia, when it is the only insecticide permitted. It must be a wonderful experience to our colleagues in Quebec to be told to use B.t. for 40% of their 1984 program and that the extra funding will be provided to maintain the same size program. Resource managers in New Brunswick phantasize about getting on the side of the angels too so it cannot be with much pleasure that our industrial managers have concluded that they can afford only chemicals on their private holdings in 1984 and that government managers once again have regretfully settled for less woodlot protection and B.t. usage than they had hoped for. It's a tough decision to opt for a hectare of B.t. spraying with the knowledge that it will deny protection to an extra hectare or two somewhere else.

Let me conclude with these thoughts. Surely much of the advocacy for B.t. in the past few years has been the kind of wheel spinning Jim Fettes warned against in summing up the Abbott symposium in 1976. Did not the CANUSA core test fit the description of the sort of scientific ad hockery he so disparaged? Some spray practitioners may have needed the evidence it provided to convince themselves that B.t. could be made to work - in New Brunswick it merely begged the real questions. Is it not regrettable that some salesmanship from scientific circles, of all places, should resort to inaccurate and unproved disparagement of chemicals while these remain so critically essential to the most hard-pressed users? Is it not still as evident as it was to Jim Fettes, that the kind of fundamental research that is needed to fully understand successes and failures has remained sadly neglected and that most of the advances made since have been principally by commercial development and empirical trial and error? So, though it may seem to be a strange reversal of roles, let a spray manager now take up the cudgel for more fundamental research as well as for better understanding of the other fellow's position.

Literature Cited

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OPERATIONAL EXPERIENCES WITH BT IN THE
EASTERN UNITED STATES

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Bacillus thuringiensis (B. t.) has been used operationally in the eastern U. S. since 1978 with most applications occurring in Maine. Changes in B. t. dosage rates, volume, cost, spray aircraft, and use patterns will be discussed. Evaluation of B. t. dosage in the east has consisted of variable results with 8 B.I.U. treatments in 1978 through 1980, to consistently good results with 12 B.I.U.'s for 1981 to 1983. Application technology has changed from high volumes in 1979 to undiluted or neat applications in 1983. Spray delivery systems have changed from boom and nozzle equipped small helicopters to small fixed-wing aircraft equipped with rotary atomizers. Improved efficacy has significantly broadened the B. t. use pattern.

Bacillus thuringiensis (B. t.) has been used as part of operational spray projects in the eastern United States since 1978. Numerous formulations and spray regimes have been employed since 1978 resulting in a substantial evolution in B. t. use patterns and spray technology. Major factors in the operational evolution of B. t. have been insecticide, dosage, volume, aircraft, spray delivery systems, spray weather guidelines, use patterns, and costs. Highlights of the evolutions of these factors in the eastern United States will be discussed in this paper.

Most operational use of B. t. in the eastern U. S. has occurred in Maine as part of the State run program or as part of other smaller operations. Most of this paper will deal with these Maine experiences. In an attempt to avoid repetition, evolution in the operational use of B. t. will be presented year by year. Changes for each of the factors mentioned above will be described for the year under consideration.

The first large scale use of B. t. in an operational program in the eastern U. S. occurred in Maine in 1978. The operation was based at Codyville in eastern Maine and covered about 22,000 acres of forest. Spraying was done with four Bell 47 series helicopters equipped with conventional booms and 80-02 nozzles. Thuricide 16B was sprayed at 8 B.I.U.'s per acre with a finished spray volume of 80 fluid ounces per acre. The operation was timed to begin at the peak of the 3rd instar, however some blocks were not sprayed until the 5th instar. The predominate host tree in the spray area was balsam fir.

Cost of the 1978 application was difficult to assess, but was certainly in excess of \$15.00 per acre; more than four times the cost of Sev-in-4-Oil applied in 1978.

The treatment area near Codyville was chosen for several reasons that reflect the beginning of a B. t. use pattern. First, the infestation level, host condition and population level, was moderate. This type of area was preferred because B. t. efficacy was not expected to equal that of chemical insecticides. The Codyville blocks included many streams, ponds and marshes and relaxed buffer policies with B. t. increased forest coverage compared to a chemical operation. Small helicopters were chosen to remove B. t. from the main airport operation since operational problems were expected and because short ferry distance with helicopters was expected to lessen the impact of high spray volumes (80 ozs.) needed. Also, the low, slow helicopters were expected to provide better deposit with a highly volatile water based B. t. formulation.

Results in 1978 were acceptable foliage protection with population reduction far less (70 to 85%) than expected from chemicals (85 to 95%). Some 1978 blocks were considered to have

only fair foliage protection. The lower level of protection in these areas was thought to be the result of poor application and wet weather following spraying.

Results of the 1978 B. t. operation were good enough to promote the further use of B. t. in Maine in 1979. Operational spraying of B. t. in 1979 covered about 38,000 acres. Thuricide 16B was used at the same 8 B.I.U.'s and 80 fl. oz. volume as in 1978. Cost of the 1979 operation was very similar to the 1978 operation.

Infestation conditions in some 1979 blocks were significantly different from conditions in 1978. As in 1978, most 1979 blocks had moderate host conditions and population, however, some blocks treated in 1979 had extreme prespray host damage and high populations. These blocks, located near Old Town, were chosen to provide information about B. t. applied under more severe infestation conditions.

The 1979 program included the use of small, single engine fixed-wing aircraft to spray some B. t. blocks, although most of the B. t. operation employed Bell 47 helicopters. Use of the fixed wing aircraft and helicopters provided an opportunity to compare the two types of aircraft and, to use B. t. in a conventional airport setting rather than a remote heliport. Both helicopters and fixed-wing aircraft used in 1979 were equipped with conventional boom and nozzle spray systems.

Operational buffering standards were formalized for B. t. in 1979. Small fixed-wing aircraft and helicopters could spray B. t. to within 1/4 mile of a house whereas 1/2 mile buffers were required for the same aircraft spraying chemicals. B. t. could be sprayed to the edge of a stream or pond, but chemicals used in 1979 required a buffer of 150 to 500 feet around water. These formal criteria made B. t. use in some areas extremely advantageous and in some areas it was the only material that could provide adequate coverage.

Results of the 1979 B. t. project were extremely variable. Results on blocks in western Maine, treated with helicopters, ranged from poor to good. Poor results were blamed on rain after treatment and late application. Results with fixed-wing aircraft varied from poor to fair. All blocks with high populations and severe tree conditions had poor results. Wet weather was not the cause of failure in the Old Town areas. These failures were attributed to poor spray deposit from the fixed-wing aircraft and high budworm populations in the blocks.

Results of the 1979 project led to two restrictions for B. t. usage. First, rotor-wing aircraft were thought to provide better spray deposit and were the favored aircraft for future applications. Second, B. t. would not be recommended in areas of high budworm population or extreme tree condition.

Operational use of B. t. in 1980 covered a much larger area (200,000 acres) than 1978 or 1979. In 1980 B. t. was sprayed as a huge demonstration project sponsored jointly by the USFS and the Maine Forest Service. Technology used was basically the same as that employed in 1978 and 1979 except that the size of the project dictated the use of more productive aircraft and use of more than one insecticide.

Large jet helicopters (Bell 204, 205, and 212) were first used for B. t. in 1980. These aircraft were capable of carrying B. t. loads of 200 to 400 gallons compared to 55 gallons carried by Bell 47 aircraft. In addition to the larger capacity, these jet helicopters were faster and sprayed wider swaths. The jet helicopters were equipped with standard boom and nozzle spray systems.

Dipel 4L was used operationally for the first time in 1980. Dipel 4L was used at 8 B.I.U.'s in 80 ozs. of final volume, identical to past applications of Thuricide 16B. Thuricide was sprayed at 80 and 128 ozs. of final volume in 1980 to determine if the high volume (128 ozs.) would improve consistency of results.

Due largely to economics of scale and insecticide competition, B. t. costs decreased somewhat in 1980. Costs were \$10.07 to \$10.51 per acre for 80 oz. applications compared to a cost of more than \$15.00 in 1978 and 1979.

Blocks chosen for B. t. in 1980 were selected on the basis of proximity to human habitation, open water in spray block, proximity to sensitive areas and moderate infestation conditions.

Results of the 1980 project were disappointing. Foliage protection and larval reductions were extremely inconsistent and not all block failures could be explained. An encouraging aspect was uniformly good deposit from large jet helicopters. Tests did show that Dipel 4L produced results equivalent to Thuricide 16B. The two spray volumes of Thuricide 16B used did not produce significantly different results.

Due largely to inconsistencies with 8 B.I.U.'s in 1978 to 1980, a number of dosage variations were tried operationally in 1981 (Table 1). Products used in 1981 were Thuricide 16B and 24B and Dipel 4L. Spray volume ranged from 80 to 120 ounces. The most important change in 1981 was the use of high dosages of B. t. as a single application of 12 B.I.U.'s and two applications of 8 B.I.U.'s. Dosage was increased to obtain more consistent results from a range of weather and infestation conditions.

Several other aspects of the B. t. program did not change in 1981. Large jet helicopters were used, and B. t. blocks were selected as before. Buffers and restrictions remained the same. The B. t. area remained relatively large,

covering 126,000 acres.

Table 1. Results of B. t. Treatment Variations By Area For the 1981 Maine Spruce Budworm Control Project

Treatment	Area	Host	% Unadj. Red.	% Def.	% Fol. Saved
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Dipel					
8 B.I.U.'s					
80 oz.	18-1	F	95.5	87	13
		S	91.5	36	2
	13-8	F	88.6	61	32
	22-16	F	97.4	58	30
		S	93.3	13	25
	SW*	F	95.8	14	14
		S	94.1	12	10
Thuricide					
8 B.I.U.'s					
80 ozs.	18-2	F**	87.9	71	29
		S	88.8	18	20
Dipel					
12 B.I.U.'s					
120 ozs.	17-1	F	91.8	(24)34	31
		S	85.2	(18)24	14
	5 Pl.	F	97.4	31	61
	**	S	96.9	23	58
Thuricide 24B					
12 B.I.U.'s					
96 ozs.	7 Pl.	F	95.3	26	60
		S	95.2	22	43
Dipel					
16 B.I.U.'s					
8+8					
80 ozs.	5 Pl.	F	95.7	50	42
		S	96.5	17	28

* Pre counts less than 10

** Pre counts 25 or more

Number in () represents omitting of a sample line which received heavy rain shortly after spray.

All areas sprayed with Bell 204 and 212 Helicopters.

In 1981 cost of an 8 B.I.U. application decreased to a range of \$7.37 to \$8.75 from over \$10.00 in 1980 due to stiff insecticide competition, more concentrated B. t. products, and lower application costs. The cost of a 12 B.I.U. treatment ranged from \$11.73 to \$12.89 depending on spray volume and insecticide used.

Results of the 1981 project were

encouraging (Table 1). While results in 8 B.I.U. areas varied from poor to good, results with 12 B.I.U.'s and two applications of 8 B.I.U.'s were consistently good. Two areas treated with 12 B.I.U.'s had good results even though budworm populations in these areas were high. Population reduction and foliage protection in 12 B.I.U. areas were not significantly different from similar areas sprayed with chemical insecticides.

It was first noticed in 1981 that B. t. was producing good results on red spruce especially at the 12 B.I.U. rate. Red spruce protection was a growing concern and chemical treatment had been only marginally effective.

The 1982 B. t. program was generally planned to confirm 1981 results, to re-evaluate small fixed-wing aircraft, to operationally assess Thuricide 32LV and Bactospiene, and to treat operationally sensitive areas with an environmentally safe product. About 89,000 acres were treated with spray variations listed in Table 2.

Table 2. Results of B. t. Treatment Variations By Area for the 1982 Maine Spruce Budworm Control Project

Treatment	Area	Host	% Unadj. Red.	% Def.	% Fol. Saved
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Dipel 4L					
12 B.I.U.'s					
120 ozs.	M72	F	95.3	36.0	44.1
Heli.		S	87.5	28.7	22.3
12 B.I.U.'s					
96 oz.					
Thrush					
w/Micro.	J5	F	98.0	10.7	25.1
		S	98.4	5.7	21.6
Thuricide 32LV					
12 B.I.U.'s					
96 ozs.					
Thrush					
w/Micro	J5	F	98.7	17.3	18.5
		S	98.9	9.7	17.6
*Bactospiene					
12 B.I.U.'s					
96 oz.					
Heli.	B13	F	91.3	12.0	22.8
		S	91.9	8.0	21.5

* This area received rain within 4 hours of application.

Most products were applied at 96 ozs. per acre, but some Dipel 4L was sprayed at 120 ozs. per acre. Cost of a 12 B.I.U. application at 96 ozs. per acre were the same as in 1981 for

Thuricide and about \$2.00 more for Dipel 4L. Cost of applying a 12 B.I.U. treatment with a small fixed-wing aircraft rather than a jet helicopter was about \$2.00 less per acre.

Fixed-wing aircraft used in 1982 were equipped with Micronair rotary atomizers rather than boom and nozzle systems. Previous tests had shown improved B. t. deposit from this type of equipment. Spray deposit results from the 1982 Maine operations showed that deposit from Micronair equipped Thrushes and jet helicopters were similar in terms of overall block coverage and droplets per unit area.

Efficacy results for 1982 confirmed 1981 results with 12 B.I.U. applications (Table 2). All 12 B.I.U. variations evaluated had good foliage protection and population reduction was similar to reductions with chemicals. Comparisons between Dipel 4L and 32LV showed no significant efficacy difference. Results with Bactospiene were inconclusive due to poor spray weather.

The effect of spray volume was compared in 1982 using Dipel 4L at 120 and 96 ozs. of final spray volume. No significant difference was found between the two volumes.

Protection of red spruce with B. t. was evaluated in 1982. Single 12 B.I.U. applications of Dipel 4L or Thuricide 32LV were found to be comparable to split applications of Sevin-4-Oil for protection of red spruce. B. t. applications were able to prevent about half the defoliation expected on the red spruce assessed.

Efficacy in 1982 on blocks treated with Micronair equipped small fixed-wing aircraft was equal to efficacy achieved with boom and nozzle equipped jet helicopters. Fixed-wing results in 1982 led to a change in the favored status held by helicopters. The decision was made to choose 1983 aircraft on the basis of price. Rotary atomizers would also be required.

A new material, volume changes, and additional evaluation of B. t. efficacy on spruce were considered during the 1983 Maine program. In addition to the 119,000 acre State run program, B. t. was applied on lands owned by the Penobscot and Passamaquoddy Indian Tribes and as a part of a large private project.

Maine added Dipel 6L to its list of operational materials (Table 3). Spray volume was reduced to 64 ounces or less for all insecticides used by the State except Thuricide 24B. Dipel 4L, Dipel 6L, and Thuricide 32LV were also applied undiluted at 48, 32, and 48 ozs. respectively. International Paper Company applied Dipel 6L and 8L undiluted in about 25% of their 1983 project. Baskahegan Company used Thuricide 32LV on their private project. The Penobscot and Passamaquoddy Indian Tribes used a variety of B. t. products on a 40,000 acre project. Finally, the State of Vermont conducted a 1,700

acre project using Thuricide 32LV, Bactospiene, and Dipel 6L. All 1983 applications in the eastern U. S. were at 12 B.I.U.'s. All applications in Maine were done with small fixed-wing aircraft at costs varying from \$5.00 to \$8.00 per acre. Cost reductions were greatest in small private projects primarily due to low project overhead. Insecticide costs were significantly lower in 1983 due to competition.

Table 3. Results of B. t. Insecticide Treatment Variations by Area For the 1983 Maine Spruce Budworm Control Project

Treatment	Area	Host	% Unadj. Red.	% Def.	% Fol. Saved
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Dipel 6L					
12 B.I.U.'s					
64 ozs.	G46	F	73.0	47.1	25.7
		S	85.5	58.7	13.5
	M82	F	93.6	44.6	43.6
		S	97.4	26.0	45.3
		H	89.3	34.1	33.8
	M72	F	81.3	12.3	18.1
		S	90.4	13.8	16.6
	M121	F	78.7	26.1	33.4
		S	79.7	20.0	41.6
		H	97.8	6.3	26.4
Dipel 4L					
12 B.I.U.'s					
48 ozs.					
Undil.	M 5	F	94.5	15.1	36.1
		S	96.4	16.4	16.4
Dipel 6L					
12 B.I.U.'s					
32 ozs.					
Undil.	M10	F	87.5	28.4	22.8
		S	86.6	20.9	11.9
Thuricide 32LV					
12 B.I.U.'s					
64 ozs.	G26	F	91.3	52.2	20.6
		S	97.4	34.1	38.1
	B5	F	88.6	45.6	27.0
		S	93.7	59.1	13.1
Thuricide 32LV					
12 B.I.U.'s					
48 oz.					
Undil.	B13	F	85.4	56.9	34.3
		S	96.9	24.3	47.9
Thuricide 24B					
12 B.I.U.'s					
96 ozs.	J12	F	91.2	33.4	45.6
		S	91.8	13.1	38.0

Table 3 Continued.

Treatment	Area	Host	% Unadj. Red.	% Def.	% Fol. Saved
<u>Bactospiene</u>					
12 B.I.U.'s					
64 ozs.	G27	F	86.7	45.6	27.2
		S	81.9	42.8	29.4

All areas were treated with Thrushes or M18 aircraft with Micronairs

Efficacy of all 1983 budworm treatments was down because of poor spray weather and unusual larval/host synchrony. However, nearly all B. t. applications conducted in 1983 were successful. Results of the Maine B. t. treatments (Table 3) were again comparable to chemical treatments. Some blocks received only fair foliage protection, but these blocks were sprayed late when much defoliation had already occurred.

Undiluted applications of Dipel 4L and 6L and Thuricide 32LV were as effective as 64 oz. applications made under similar conditions. Spray deposit with undiluted materials was comparable to deposit with 64 oz. applications.

Protection of red spruce with B. t. was good for the third consecutive season. Defoliation on spruce was unusually severe in Maine in 1983, but B. t. applications were able to reduce defoliation to 50% of expected in most blocks.

To summarize, the six years of operational B. t. usage have led to substantial changes in B. t. usage patterns in Maine. It seems appropriate to end this paper with the current status of B. t. application in Maine and the eastern U. S..

Dosage - The 12 B.I.U. dosage is generally accepted in Maine and the eastern U. S.. This rate has a nearly perfect record of success over three years of use. A change from 12 B.I.U.'s to a lower rate would require significant evidence.

Material - Currently available materials favored for use in the eastern U. S. are Bactospiene, Dipel 4L, 6L, and 8L, and Thuricide 32LV and 48LV.

Volume - Low spray volume is generally accepted. Volumes of 64 ozs. have been proven as effective as high volumes used in the past. The Maine State program favors undiluted applications at 48, 32, or 24 ounces depending on which product is used.

Cost - B. t. costs have shown large reductions since 1978 due to competition, concentrated products, and lower emission rates which

lower application costs. B. t. costs are now close to the cost of Sevin-4-Oil, but remain significantly higher than the cost of Matacil or Zectran.

Aircraft - Small fixed-wing aircraft are now preferred as a less expensive, but effective alternative to helicopters.

Spray Delivery System - Micronair atomizers are preferred to boom and nozzle systems.

Efficacy - Foliage protection and population reductions on spruce with 12 B.I.U.'s of B. t. have been comparable to chemical results. Results with B. t. on fir are not usually different from chemical results, but in an exceptional year, chemical results of fir can be significantly better.

Timing - B. t. has been effective from the mid 4th to early 6th instars. Early timing is restricted by need for bud expansion to provide a foliar target. Spray applications during late instars are restricted by the amount of prespray damage.

Operational Considerations - Undiluted B. t. materials do not present any unusual operational problems. However, bulk shipment would be an improvement.

Usage Patterns In Maine

1. Can be used on any level of budworm population
2. Often favored on areas with a high spruce content (70% spruce)
3. Not favored on fir in critical condition
4. Favored in wet areas where chemical buffers hinder spray coverage
5. Favored near environmental hazards
6. Favored near human habitation
7. The percentage of the Maine spray project treated with B. t. has shown a gradual increase since 1978.

Year	Approximate Acreage	Percentage of Operation
1978	20,000	1
1979	38,000	2
1980	200,000	15
1981	126,000	11
1982	89,000	10
1983	119,000	14
Planned		
1984	250,000	30

Operational Weather Guidelines

1. Should not be sprayed when cool, wet weather is predicted shortly after spray
2. Best results are expected when warm, dry conditions are expected for a day or two after spray
3. Weather requirements are more restrictive than those for contact chemicals due to the quicker action of chemicals

FOUR ENGINE AIRCRAFT EXPERIENCE IN THE APPLICATION OF BACILLUS THURINGIENSIS AGAINST THE SPRUCE BUDWORM IN QUEBEC

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Introduction

I want, during this presentation, to give you a spray program coordinator point of view on Bt and try to explain why things are always different in Quebec. Not always better but always different, even in the application of Bacillus thuringiensis where 4 engine aircrafts were used to control the spruce budworm, Choristoneura funiferana (Clem.), infestation.

First, a background of the situation is required: background of the Quebec forest and background of our perception of Bt. In order to progress in our approach to use Bt, some KEY FACTORS and GOALS have been established. This brought us into two major periods in the use of Bt: the 1971-1980 period where we learned to live with Bt and its constraints, and the 1981-1983 period where some of the constraints have been solved to a certain degree. Finally, the 1984 project is discussed.

Background

To fully understand the approach, it is important to know that 95% of the Quebec forests are crown lands which are leased to forest industries for wood supply. In order to keep the industrial activity going, one of the tasks of the Quebec Department of Energy and Resources is to organize protection programs against any forest enemies. In the perspective of spruce budworm infestation which attacked softwood species, the major component of the Quebec forest economy, this meant protecting a very large area during a short period of time, the period of the year where the insect was active (6 weeks), in parts of the province where roads and airstrips were scarce. This situation led us to organize spraying programs on large blocks of continuous forests on crown lands, while other approaches like salvation cutting were organized on more accessible but patchy private woodlots. In this strategy, the use of large aircrafts with large capacity payloads was the only alternative available to achieve adequate protection.

The major species attacked by the budworm in Quebec is balsam fir. White spruce and, to a minor degree, red and black spruces are also attacked but being not an important part of the softwood volume, they are not considered in our approach with respect to timing, efficacy and damage.

Programs were initially conducted in western Quebec where the infestation was first reported but by the mid seventies, as the infestation moved from west to east and covered the whole province, the treatments were concentrated in eastern Quebec, where the most important softwood forests were located.

The fact that Bt is a living organism had a major influence on our techniques used to evaluate spray deposit and on mixing procedures. Petri dishes with gelose were used on the ground to evaluate deposit in term of colonies/cm², without any reference to size of droplets because the addition of dye (needed for drop sizing) could affect the viability of the spores. Likewise, the addition of water for final formulation was done just prior to application, to avoid activation of the spores.

Key Factors and Goals

In order to evaluate progress achieved thru years with Bt, the treatments had first to be characterized, then some KEY FACTORS were chosen to evaluate efficacy, GOALS were set up as bench marks for what we considered adequate results.

The important points chosen for the characterization of treatments were:

- areas treated (hectares)
- type of Bacillus thuringiensis (oil and water basis)
- concentration of the initial formulation (BIU/litre)
- volume used (litre/ha)
- dosage (BIU/ha)
- final formulation (%)
- type of aircraft used (altitude (meter)
(speed (Km/s)
(capacity (litre)
(swath (meter)
(pressure (litre/s)
- navigation system
- spraying system
- weather condition
- timing (Insect and shoot development)

The KEY FACTORS that were examined to evaluate the efficacy of the treatment were:

- Pre spray population (larvae/45cm branch)
- Residual population (pupae/45cm branch)
- Larval mortality (at peak pupae)
- Previous damage (years of severe defoliation)
- Annual defoliation
- Deposit (number of colonies/cm²)
- Synchronization of insect and shoot development.

GOALS

The treatments were conducted to reduce stress on the trees and to keep the forest alive. Experience with chemical insecticides told us that, as long as the annual defoliation was kept below the 50% threshold, a treatment could be considered as adequate and successful.

THE 1971-1980 PERIOD: Learning to live with Bt and its constraints

When the spruce budworm infestation was first reported in Quebec during the late sixties, *Bacillus thuringiensis* (Bt) was the only biological alternative to chemical insecticides. Under the technical advice of the Laurentian Forest Research Center, the Quebec Department of Energy and Resources initiated in 1971 some experimental work with Bt.

On a trial and error basis, it soon appeared that the application of Bt was more sensitive than the application of chemical insecticides. Detailed treatments conducted from 1971 to 1980 have been described in detail in an earlier presentation (Dorais and al. 1980) and the major conclusions that could be drawn from that period were that:

- good results with Bt have always been associated with good deposit. A spray deposit of 20 colonies per cm² collected on petri dishes was the rule of thumb to consider a treatment to be effective;
- spray volume required to achieve such a deposit varied from 4.68 (for single engine) to 7.0 l/ha (for four engine aircraft). Under those circumstances, a dosage of 20 BIU/ha could adequately control population levels up to 25 larvae/45cm branch;
- timing also appeared to be very critical. As a stomach insecticide, Bt has to contaminate the annual foliage and has to be ingested in order to kill the larvae. No treatment could be done prior to bud flare and, on a block basis, a treatment conducted within 10 days after the bud flare could be considered as adequate. On a spray program basis, like in eastern Quebec, 20 days was the usual maximum period available per year to apply Bt for proper timing;
- products manufactured became more concentrated thru time (16 to 32 BIU/USG) to suit forestry needs: these more concentrated formulations increased the plane efficiency per year and the area treated could then be increased (Table 1);
- since spores are activated after 12 hours in water, the final formulation was prepared only when the block was ready and when we were absolutely sure that the product could be applied. 30 minutes of mixing time was then required prior to application. This procedure limited the use of Bt to one load per spray period;

- oil base formulations diluted in water required a higher volume to be sprayed than water base formulations, because the amount of water needed in the final formulation had to be at least equal to the amount of oil to avoid inverted emulsion;

- planes used thru the years were: Stearman, TBM Avenger, CL-215, Constellation L-749, DC-6B, and DC-4G. The larger planes came into use to improve spray load capacity.

The 3 major constraints that limited our confidence in Bt at the end of this period were:

- the poor efficacy against high populations (population > 25 larvae per 45cm branch)
- the poor plane productivity (efficiency) per year
- and the cost of the treatment; still 3 times more expensive than a double application of chemical insecticides

Resulting Spray Policy

Even as all efforts were oriented to increase the area treated annually, results obtained were highly variable and the use of Bt was limited to highly sensitive areas where chemical insecticide could not be applied.

Based on experience the norms followed to achieve good results with Bt were:

- population level > larvae/45cm branch tip
- dosage 20 BIU/ha
- volume 4,68 l/ha for single engine aircraft
7,0 l/ha for four engine aircraft
- deposit 20 colonies/cm²
- timing 0 to 10 days after bud flare
- cost of treatment (1981): \$9.48 for chemical treatment and \$31.43 for biological treatment.

Based on the payload of a DC-4G (20 000 lbs) at the rate of 7 l/ha, one plane could normally treat (over a 20 day period) 24 000 hectares per year compared to 125 000 hectares (x2) with chemical insecticide.

The 1981-1983 Period: Solving The Bt Constraints

During the period of 1981 to 1983 some new highly concentrated formulations have been developed and tested in the field. It was expected that the droplets produced, being more concentrated, could kill the insect faster than the former diluted formulations and could therefore reduce the damage caused. At the same time, a smaller amount of material being applied per hectare would increase the annual plane productivity.

Tests were conducted with one of these concentrated formulations (FUTURA 51 BIU/USg). Applied in a volume of 2.5 l/ha, this concentrated formulation for 2 years in a row gave very good larval mortality plus an overall striking degree of foliage protection, even against population levels as high as 35 larvae per 45cm branch tip. These observations changed completely the picture of our aerial spraying programs with Bt. The major changes were:

- limitations for the concentrated Bt, regarding population levels, seemed to be identical to chemical insecticide; concentrated Bt in fact performed as well as chemical insecticides against population levels as high as 35 larvae/45cm branch tip;
- dosage of 20 BIU/ha provided adequate results in tests conducted in Quebec with FUTURA while in other provinces or states a dosage of 30 BIU/ha seemed to give more consistent results; 20 BIU/ha was considered then as a marginal dosage that could be successful if other factors like timing, deposit, etc. were favorable. Volumes lower than 2.37 l/ha never gave adequate deposit with 4 engine aircraft, so dosage was chosen in order to respect the 2.37 l/ha volume limit;
- deposit of 10 to 15 colonies per cm² could be considered adequate; since droplets were more concentrated, a fewer number was required for good results, compared to diluted material. Meanwhile, in order to improve spray technology, an experiment was carried out to correlate deposit with foliage protection (without success!). This raised questions about the colonies per cm² in petri dishes as a valuable technique, and left the question about ideal size and concentration of droplets that should be generated (the smaller size droplets collected on foliage contained a lethal dosage) unresolved.
- oil-base concentrated formulations when applied undiluted (neat) have an advantage over water-base formulations, with respect to payload. Oil being lighter than water, a higher volume could be carried by the plane per load compared to water-base formulation. On the other hand, plugging problems have been encountered with oil-base material when water, created from condensation in the tank, produced an inverted emulsion with oil (Table 2);
- because concentrated formulations were applied undiluted, mixing procedures were simplified. The product was stable by itself and required only agitation to make an homogeneous suspension prior the application. Without elaborate mixing procedures just prior to application, two loads per spray period could be planned, weather permitting, the same as for chemical insecticide applications.

The 3 major constraints that were discussed from the previous period were reduced to a certain degree with the new concentrated formulation. That is:

- improved efficacy against high larval populations
- an increase in plane efficacy each year (by 2 to 3 times)
- the cost of treatment was still 2 times more expensive than the cost of a double application of chemical insecticide, but the cost of the B.t. product has been decreasing for 2 years in a row, as a result of larger scale economics based on more confidence in the reliability of B.t.

Planned 1984 Spraying Program

After 13 years of research and development to utilize Bt on large scale budworm spraying programs, the Quebec Department of Energy and Resources decided that the major improvements achieved in the three past years warranted giving Bt an honest try; thus, 300 000 of the 800 000 ha contemplated for 1984 will be treated with Bt (200 000 ha with undiluted material and 100 000 with diluted material).

The criteria now recognized to achieve good results with Bt are:

- population level: < 35 larvae/45 cm branch tip
- deposit: 10 to 15 colonies/cm²
- volume: 2.37 l/ha (undiluted) to 4.68 l/ha (diluted)
- dosage: 20 to 30 BIU/ha
- timing: 0 to 10 days after bud flare
- cost (1983): \$10.99 for chemical treatment
\$26.86 for biological treatment

So, in 1984, based on the payload of a DC-4G (20 000 lbs) at the rate of 2.5 l/ha, one plane could treat over a 20-day period a total of 65 000 to 83 000 hectares, compared to 125 000 hectares using chemical insecticides (Table 2).

Planned 1984 Experimental Program

In order to keep improving Bt control for spruce budworm, our research priorities for 1984 have been established as:

- to develop a reliable spray deposit technique which can be correlated with foliage protection;
- to investigate the ideal droplet size and concentration (i.e. the smallest droplet which contains a lethal dose);

- to test in the field some formulations of Bacillus thuringiensis Kurstaki (isolate HD-1) concentrated at 64 BIU/USg and a new isolate (NRD-12), potentially more toxic for the budworm than the former HD-1.

Conclusions

Technological development of new formulations which increased efficacy of Bt and plane efficiency, the growing pressure of the larval population that survives in the forest to cause increasing tree mortality, and the collective history created about chemicals by uniformed people, are the factors which have contributed to greater use of Bt. B.t. still remains the only operational biological alternative to chemicals for spruce budworm control.

The growing use of Bt generated an important diversified expertise. Research programs, like CANUSA, have helped by a joint effort to sort out the good and bad experiences, but the important thing is that a climate of confidence has been created towards B.t. by users and producers. With all this interest generated, major improvements are still to come in the near future: increased toxicity and effectiveness at a lower cost.

References

Dorais, L.; Pelletier, M.; Smirnoff, W. Aerial spraying applications of Bacillus thuringiensis Berliner conducted on Quebec forests (CANADA) from 1971 to 1979 against the spruce budworm, Choristoneura fumiferana (LEPIDOPTERA TORTRICIDAE) Vith International Agricultural Aviation Congress held in Turin, Italy, September 1980.

Table 1.--Comparison of aerial applications of Bacillus thuringiensis cconducted in Quebec from 1972 to 1980

Year	Area treated (ha)	Concentration (BIU/USg)	Volume (/ha)	Aircraft used
1971	80	16B	18,72	Stearman
1972	4000	16B	18,72	TBM Avanger
1973	120	26B	4,6	CL 215
				TBM Avanger
1974	3250	26B	4,6	DC 6B
				CL 215
1975	91000	16-26-36	2,3 - 4,6	DC 6B
1976	120	32B	4,7	S-55T Helicopter
1977	NONE	---	---	---
1978	13300	32B	9,36	DC 6B
			4,68	Ag Cat B
1979	17030	32B	4,68 - 7,0	L-749
1980	22180	32B	7,0	L-749

Table 2.--Alternative treatments of *Bacillus thuringiensis* for 1984

Product	Concentration (BIU/USg)	Dosage (BIU/ha)	Volume (ℓ /ha)	Plane productivity (ha/year)
Thuricide 32LV and Novabac-3	32B	20	2.37 (neat)	70 040
		20	4.68 (diluted)	42 740
		30	3.55 (neat)	46 760
		30	7.01 (diluted)	28 580
Dipel 88	32B	20	2.37 (neat)	83 540
		20	5.85 (diluted)	32 000
		30	3.55 (neat)	55 780
		30	8.84 (diluted)	22 500
Futura TM	51B	20	2.5 (diluted)	65 600
		30	3.75 (diluted)	43 740
Thuricide 48LV	48B	20	1.58 (neat)	105 060
		30	2.37 (neat)	70 040
Dipel 132	48B	20	1.58 (neat)	125 320
		30	2.37 (neat)	83 540

VIEW OF FOLIAGE PROTECTION SPRAY OPERATIONS

AINST THE SPRUCE BUDWORM WITH BACILLUS

URINGIENSIS KURSTAKII FROM 1980 TO 1983 IN

VA SCOTIA AND NEW BRUNSWICK, CANADA

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Spray operations against the spruce budworm have been conducted in New Brunswick in 1980, 1982 and 1983 and in Nova Scotia from 1980 to 1983. The results obtained in terms of foliage protection have been extremely variable. Attempts to pinpoint the causes for this variable result suggest that a number of factors are responsible. These are weather during and after spraying and sampling problems.

Introduction

The purpose of this paper is to review the usage of Bacillus thuringiensis kurstakii (B.t.k.) in foliage protection programs against the spruce budworm (Choristoneura fumiferana Clem.) in New Brunswick and Nova Scotia and attempt to pinpoint the reasons for the frequent failures in foliage protection. Operational foliage protection spray programs using commercial formulations of B.t.k. were conducted in Nova Scotia from 1980 to 1983, and in New Brunswick in 1980, 1982 and 1983. In Nova Scotia B.t.k. was the only material allowed for use against the spruce budworm on large tracts of forests while in New Brunswick both B.t.k. and chemical insecticides were used. In New Brunswick B.t.k. has been used only in the foodlot protection program (along with chemicals) in an attempt to provide protection to select stands of fir and spruce.

There is a trend to increased use of B.t.k. throughout eastern Canada so it is important to try and understand why the results are so erratic. This type of performance plus the higher cost of spraying B.t.k.'s offset the environmental advantage of them, hence there is a reluctance to use more B.t.k.

Assessment Of Efficacy

In both Nova Scotia and New Brunswick efficacy in terms of foliage protection is estimated by comparing the level of defoliation in treated and unsprayed control plots with similar pre-spray spruce budworm population densities. Pre-treatment densities of larvae are determined for one 45cm. branch tip per sample tree. The branches are taken from the mid-crown area of the selected trees.

In Nova Scotia defoliation for each sample tree (fir or spruce) is assessed by classifying the level of defoliation on each of forty shoots per tree using the Fettes method (Dorais and Kettela, 1982). In New Brunswick defoliation on balsam fir (Abies balsamea Mill.) is estimated for the whole tree crown using methodology developed by Webb (1956). However for **spruce** (Picea sp.) defoliation is estimated as either nil, light, moderate or severe. In the case of the spruces it is the authors opinion that both methods used are inadequate in estimating defoliation on spruce, particularly the red/black hybrid complex.

Unsprayed control data are used to generate graphs showing the relationship between larval population density and resultant defoliation. These relationships need to be examined each year as the degree of defoliation **caused** by a given population of larvae varies from year to year on both species of trees (Fig. 1&2).

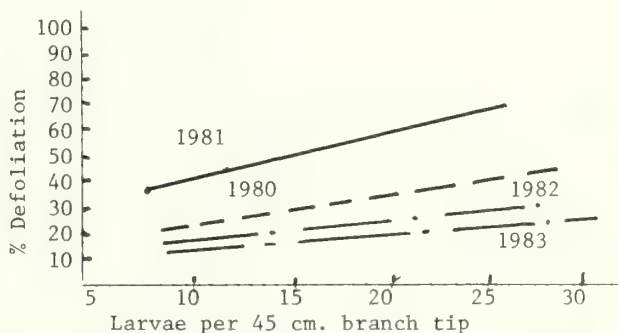


Figure 1. Defoliation as a function of early instar spruce budworm larvae per 45 cm. branch tip on red/black spruce in the Maritimes region of Canada.

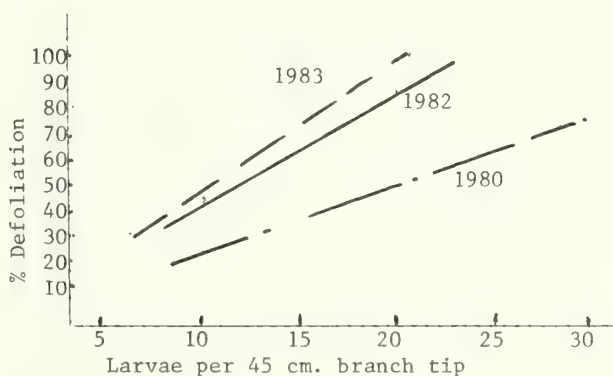


Figure 2. Defoliation as a function of early instar spruce budworm larvae per 45 cm branch tip on Balsam fir in the Maritimes region of Canada.

It is apparent from Figures 1. and 2. that fewer budworm larvae cause more defoliation on balsam fir than on spruce.

Foliage protection due to treatment can be estimated a number of ways; first as simply the difference between expected defoliation and observed defoliation, secondly by using Abbott's formula(Doraís and Kettela, 1982) which is

$$\frac{\text{expected defoliation} - \text{observed}}{\text{expected defoliation}} \times 100\%$$

and thirdly as the difference between observed defoliation and 100%. This last method estimates total foliage retention **which though** very important to the tree is a poor measure of efficacy. Essentially it is possible to generate three estimates of foliage protection from the same set of data. This is an important consideration when arbitrary values for good foliage protection are established such as those in New Brunswick and Nova Scotia.

Two important factors that influence efficacy are the stages of development of larvae and shoots at the time of spray application. At this point in time there is some disagreement as to the appropriate timing for good foliage protection on fir and spruce. It is generally accepted that the shoots on balsam fir should be starting to flare when B.t.k. is applied. This more or less coincides at the peak of fourth instar development. In Nova Scotia, where considerable areas of red/black spruce are sprayed, spraying is commenced when the buds of spruce have started to swell and the bud caps have fallen off. This more or less coincides with development of larvae between fifth and sixth instar. Delays in spraying caused by weather when this type of late timing is used can result in poor foliage protection. Apparently adequate foliage protection of spruce has been obtained at a considerably earlier timing of B.t.k. sprays. How this works is not understood.

Results Of B.t.k. Applications In New Brunswick

1980

In 1980 10 521 ha were treated with either Thuricide 16B or Novabac-3 at a dosage rate of 20 B.i.u's per ha in 11.5 l per ha. Three spray systems were used ; fixed wing aircraft with boom and nozzle spray equipment, fixed wing aircraft with Micronaire rotary atomizers and a rotary wing aircraft equipped with boom and nozzle spray equipment.

Of the 251 woodlots sprayed 148 were sampled to determine efficacy of spraying. Results of this investigation are detailed by Kettela and Steel (1984). Essentially, the results in terms of foliage protection were extremely variable. From 40 to 60% of the woodlots had a detectable level of foliage protection, depending on the region in New Brunswick. Analysis of the data showed no clear relationship between efficacy and timing aircraft type, spray system used or forest composition and condition. Interestingly red/black

was apparently better protected than balsam fir. In light of experiences in 1983 with red/black spruce sampling the result noted in 1980 may be due simply to inadequate sampling of spruce. Further, the mediocre result may have been due to the dilution rate of B.t.k.

1982

In 1982 4 000 ha of forest were treated with B.t.k., 3 200 ha operationally with Dipel 88 and 800 ha in a test program with Novabac-3 and Bactospeine.

With respect to the Dipel 88 treatment one half of the area was treated at 20 b.i.u. per ha and the other half at 30 b.i.u. per ha. Sampling for efficacy was concentrated in that area treated at 30 b.i.u. per ha. The results (Table I) showed that although there was excellent larval mortality foliage protection was very poor.

Table I. Results of spraying Dipel 88 undiluted at a rate of 30 B.I.U per ha in New Brunswick, 1982.

	Budworms/ 45 cm branch		Development Index		Defoliation %	
	larvae	pupae	shoots	larvae	Observ.	Expt.
<u>Balsam Fir</u>						
Treated	19	0.4	5.0	4.5	70	84
Control	20	2.6				
<u>Red Spruce</u>						
Treated	18	0.3	1.5	3.4	50	50
Control	16	0.5				
<u>White Spruce</u>						
Treated	17	0.9	5.0	3.8	75	75
Control	25	1.5				

Easy explanations for this result are not forthcoming. By all measures conditions for spray application were excellent, weather conditions were good, before, during and for days after the spray, and shoot and larval development were optimum.

1983

In 1983 some 10 117 ha of irregular shaped woodlots of from 25 to 500 ha were treated with Novabac-3 at a rate of 30 b.i.u./ha in 4.7 l/ha. The bulk of the area treated was located in the Fredericton area (central N.B.), with small areas located in southern NB by the Fundy Coast, and in northern NB south of Campbellton. Spraying was done with small agricultural type fixed wing

aircraft equipped with Micronaire AU 3000 rotary atomizers.

Spray efficacy was estimated from pre-spray larval counts on both balsam fir and spruce (usually red/black spruce), and post spray estimates of defoliation. Three blocks in northern N.B. were sampled for just post spray defoliation. Development of shoots and larvae were estimated from the appropriate graphs. A summary of the results is shown in Table II. Red/black spruce data is omitted because of its inconclusive nature.

Table II. Summary of spray results with B.t.k. (Novabac-3) on woodlots in New Brunswick in 1983.

Shoot Development Index	Pre-spray Larvae per 45 cm branch	Defoliation %	
		observed	expected
3.1	2.2	80	10
3.1	4.7	80	30
3.1	4.9	30	35
3.1	5.2	80	40
3.1	12.3	60	72
3.4	7.5	10	60
3.4	8.1	100	61
3.4	9.8	20	65
3.4	13.6	100	78
3.9	3.8	60	20
3.9	5.7	60	45
3.9	7.7	60	60
3.9	20.4	10	90
4.0	11.5	30	67
4.4	11.1	50	66

spray blocks in northern NB			
4.5	high	20	70+
4.5	high	10	70+
4.5	high	30	70+

Of the eighteen blocks sampled only 10 had a detectable level of foliage protection. There appears to be a weak relationship of better foliage protection with increasing shoot development. Examination of weather records showed that all the blocks sprayed in the Fredericton area were treated during a cold wet spell where there was rain most every day and mean daily temperatures of 16°C. It is suspected that this weather inhibited larvae from feeding and retarded shoot growth. Further, the irregular shape of the blocks made it difficult to spray the areas accurately. Similarly poor results were obtained on woodlots in the Fredericton area treated with the chemical fenitrothion. However, the three spray blocks in northern N.B. seem to have been adequately protected. Post spray weather for these blocks was generally warm with no rain for at least two weeks.

Results of B.t.k. Spraying in Nova Scotia

An experimental spray program to provide foliage protection to balsam fir and spruce was carried out in 1979. This program was apparently very successful and set the stage for operational usage of B.t.k. against the spruce budworm in Nova Scotia. Initially spray operations were concentrated on Cape Breton Island but were expanded to include red spruce forests in Cumberland and Colchester County in western Nova Scotia. From 1981 to 1983 spray operations were concentrated there. Although considerable data exist on spray effects on balsam fir, it is the spruce data that is particularly interesting. Details on area sprayed, costs and related items are presented in a report edited by J.R. Carrow (1983).

The spray format followed for the past three years has not varied, although a variety of B.t.k. formulations were used. Spray applications were started when red spruce buds started to swell and lose their bud caps. Larval development on average was between the fifth and sixth instar. Ag-cat spray aircraft with standard boom and nozzles were used. Swath width was a nominal 30 meters per aircraft and they flew in formations of two or three planes. The dosage used was 20 b.i.u./ha in 4.7 l/ha.

Of the spray blocks examined here, four were sprayed for the past two years, two for the past two years, and two for the first time in 1983. This provides an opportunity to examine protection applied consistently over time (Table III). Blocks were selected for protection based on tree condition, stand type and egg-mass infestation. Timing and weather are not overriding factors for all blocks were sprayed within guidelines established for the program.

It is evident from Table III that there was a large difference between observed defoliation and expected defoliation in 1981, indicating that the B.t.k. application provided a measurable level of foliage protection. However in 1982 and 1983 the difference between observed and expected defoliation was considerably less. This does not mean that there was a decrease in the effectiveness of the B.t.k. applications in 1982 and 1983. In fact, in view of the guidelines set down for adequate foliage protection, this is the case. Figure 2 shows clearly that less defoliation was caused by similar larval densities in both 1982 and 1983 than in 1981. Observed defoliation was generally low in all blocks in all years. This problem with spruce is a recurring thing and greatly affects the way data on spray efficacy are analyzed. Similar results were obtained on spruce in New Brunswick in 1983. This spruce sampling-interpretation problem must be acknowledged particularly when analyzing data from experimental spray trials. It would be very easy to draw the wrong conclusion on efficacy.

In general the efficacy of B.t.k. against the spruce budworm has been mixed with good results in 1981 but apparently poor results in both 1982 and 1983.

Table III. Results of spraying B.t.k. at 20 b.i.u per ha on selected red spruce stands in Cumberland and Colchester Counties in Nova Scotia from 1981 to 1983.

Location and Year	Pre-spray Larvae per 45 cm branch	Defoliation	
		Observed	Expected
Advocate			
1981	18	18	49
1982	37	28	41
1983	26	27	29
Shulie			
1981	19	16	52
1982	38	29	42
1983	14	24	16
Moose River			
1981	17	15	47
1982	14	8	18
1983	4	9	4
Economy			
1981	9	8	36
1982	10	5	11
1983	9	7	10
Welton Lake			
1982	33	30	39
1983	21	21	23
Eatonville			
1982	31	30	39
1983	6	7	7
Chicnecto			
1983	20	21	22
Sand River			
1983	33	14	37

Conclusions

Looking for the clues as to why B.t.k. at times gives poor results, or apparently poor results is a frustrating task. The reasons for failure can range from poor timing, to bad weather following application, block size and configuration, and an inability to separate cause and effect because there is no apparent difference between treated and non-treated stands of trees.

Certainly, in the New Brunswick experience in 1983 cold wet weather seemed to be the cause for the poor result in those blocks sprayed in central N.B. Delaying spraying to take advantage of forecasted good weather seems to be at best a very hazardous option. The longer you wait to apply B.t.k. consigns at least some of the foliage you want to protect to the budworm. This is particularly so when budworm larval populations are very high.

Sampling and data interpretation problems appear to be particularly acute with red/black spruce. Sampling systems currently being used are apparently not sensitive enough to at times

clearly show the differences between treated and non-treated areas. This is true for areas treated with chemicals as well.

Studies that are to be reviewed elsewhere in this symposium point to deposit as a key factor in the performance of B.t.k. as well as the concentration of B.t.k. in each drop. Surely development of more stable formulations with stickers and more potent Bt. strains will remove some of the chance out of protection operations with B.t.

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COMPARISON OF BT
FORMULATIONS AGAINST
THE SPRUCE BUDWORM

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SUMMARY

The Passamaquoddy Indian Forestry Department treated 40,300 acres in Maine in 1983 using Bt to protect red spruce and eastern hemlock from spruce budworm damage. The post treatment evaluation indicated that the protection objectives were achieved. In cooperation between the Passamaquoddy Indian Forestry Department and two commercial Bt suppliers, Abbott Laboratories and Zoecon Corporation, four commercial products were applied as eight field formulations. Where possible, these treatments were compared for effectiveness. The results show an average defoliation of 23 percent and population reduction from 864.5 budworms per 100 square feet of foliage to 62.5 budworms, or an average of 94 percent population reduction. The undiluted field formulations gave significantly ($P = 0.05$) less defoliation and greater population reduction than the diluted formulations. A method for spray deposit assessment using spruce foliage is presented.

INTRODUCTION

McCreery (1982) reported high spruce budworm populations and heavy past damage on about 40,000 acres of Passamaquoddy Tribal Trust lands. The Passamaquoddy Indian Forestry Department (PFD) requested and obtained spruce budworm suppression funds. USDA Forest Service, Durham Field Office staff provided technical assistance to the PFD in implementing and evaluating the suppression project. An earlier report summarized the suppression project accomplishments (McCreery and Francis 1983). In this report, various Bt field formulations used on the project are compared.

PROJECT AREA

The project was conducted in SBW-infested spruce and hemlock stands on Tribal Trust land in Townships T4ND BPP, T5ND BPP, T5R1 and Indian Township, Maine. These lands, most of which were only recently purchased by the Tribe, have been infested by SBW for many years. Only a small portion of the lands has been protected in the past.

The total area sprayed was about 40,300 acres. This area was in 26 blocks ranging from 500 to 4,000 acres. Blocks were delineated on the basis of biological need for treatment as well as topography and forest cover to aid in navigation.

METHODS

Insecticides

Four commercial preparations of Bt were used: Dipel 6L and 8L (Abbott Laboratories), and Thuricide 32LV and 48LV (Zoecon Corporation) (Table 1). All materials were applied in various field formulations from undiluted to 95 fl. oz. per acre to give 12 BIU's of active ingredient per acre. The only exception was Dipel 8L, which was applied undiluted at eight BIU's per acre (16 fl oz/acre). A sticker, RA-1990 (Rohm and Haas) was added at 2% rate of field formulation for all dilute applications.

Mixing and Loading

Mixing and loading services were provided by Chem-Pro of Oregon as subcontractors with Biegart Aviation.

Two semi-trailer tankers, each equipped with three compartments, were used to mix the insecticide. Dipel and Thuricide were mixed in separate tankers to avoid problems of incompatibility. Insecticide was unloaded from 55-gallon drums and stored in one of the compartments and water was stored in the other. The third compartment was used to mix the insecticide as needed. All liquids were metered as they were pumped to the compartments and to the aircraft. Insecticides were used within 24 hours after mixing. The sticker was added to the water before the addition of insecticide. No mixing problems occurred with the sticker.

Table 1.--Products used during the 1983 Passamaquoddy Suppression Project

Product	Rate (fl oz/acre)	Gallons Sprayed	Acres Sprayed
Dipel 6L	32	935	3740
	65 ^{a/}	5277	10344
	96 ^{a/}	3000	3960
	Subtotal	9212	18044
Dipel 8L ^{b/}	16	110	900
Thuricide 32LV	48	741	1976
	64 ^{a/}	2295	4590
	96 ^{a/}	8764	11685
	Subtotal	11800	18251
Thuricide 48LV	32	782	3128
	Grand Total	21904	40323

^{a/} A sticker, RA-990 (Rohm and Haas), was used with all dilute applications at a rate of two percent by volume.

^{b/} Dipel 8L was donated by Abbott Labs for use on this project.

Aerial Application

The aerial application was done by Precision Air of Foley, AL, as subcontractors to Biegart Aviation, Mesa, AZ. The aircraft were based at Princeton Airport, Princeton, ME. Spraying started on June 1, 1983 and was completed on June 9, 1983. The spray blocks were from 2 to 35 air miles from the airport.

Aircraft and Spray Equipment

Three aircraft each with a spray volume capacity of 300 gallons were used. One was a Thrush 600; the others were Snow Thrushes. All three were equipped with eight Mini-Micronair rotary atomizers (AU 5000). Atomizers were equally spaced along the boom, beginning 18 inches from the outboard end. Atomizer pitch was set at 45°.

Aircraft Calibration and Characterization

The aircraft were calibrated at Princeton Airport on the basis of data from spray trials in Foley, AL (O'Neal 1983). At the spray trials, Thrush 600 aircraft were flown at 110 mph, 50 feet above target at pump pressure of 40 psi. Twenty drops/cm² was the minimum standard for locating an effective swath at the Foley trial. Thuricide 48LV did not provide the 300 foot swath width at Foley, but later achieved that swath during tests at Princeton Airport. A swath width of 300 feet was used for all formulations.

Application

The three aircraft sprayed as a team. Team guidance was provided by a guide ship (Lincoln Air) equipped with a Loran C guidance system (Teledyne Corp.), which was used to locate team swaths. A

monitor and spotter, both PFD employees, observed all applications from the monitor aircraft (Lincoln Air) 800 to 1000 feet above the terrain. The spotter called booms-on, booms-off over treatment areas. The monitor observed spray cloud behavior, team spacing, and weather conditions.

Meteorology

Weather conditions were monitored by ground personnel within treatment areas, the monitor aircraft, and through long range forecasts provided by the Maine Forest Service and Bangor International Airport Flight Service. The work plan specified these weather conditions as acceptable for Bt application:

- Drip dry foliage within or in close proximity to spray blocks.
- No rain forecast for four hours.
- Windspeed >2 mph but <15 mph.
- No inversion conditions present at or below 100 feet above canopy.
- Air temperature forecast to be 55°F or higher within 36-48 hours.
- Air temperature above 32°F at application time.

Larval and Bud Development

Larval and bud development were monitored at eight sites - five in the spray areas and three in the check areas. At each site, five codominant spruce were marked for development sampling. Each sample consisted of one 36-inch branch cut from the midcrown and brought to the field laboratory. Collections were made at three to five day intervals until spraying was completed. Laboratory examinations were completed on the same day as collections.

In the laboratory, all larvae (not more than 100) found on the branches were removed and their location recorded as:

- Wandering on branches.
- Mining in the needles.
- Mining in the buds.
- Other (loose in the bag, etc.).

Larval instars were determined from head capsule measurements and body coloration. Larval index was determined by the method described by Dorais and Kettela (1982). The results are summarized in Tables 2 and 3.

Bud development index is shown in Table 2. This system was developed by D. G. Mott, formerly of the PFD staff. The classes were defined as:

- Class 1 - Tight buds, no green showing at the base of the bud.
- Class 2 - Bud expanding, <2mm of green showing at the base of the bud.
- Class 3 - Bud expanding, >2mm of green showing at the base of the bud.
- Class 4 - Bud cap off.

Insecticide application was timed to start when most of the larvae had left needle mines (more than 50%).

Table 2.--Larval and bud index values for the Passamaquoddy Spray Project (first and last spray day), 1983

Location	June 1		June 9	
	Larval Index	Bud Index	Larval Index	Bud Index
T4ND 1	3.4	1.0	4.0	2.5
2	3.0	2.1	4.0	3.3
3	3.0	1.0	4.0	2.0
T5ND 1	3.0	1.0	3.8	1.2
2	3.5	1.5	4.6	2.5

Table 3.--Larval behavior during and after the Passamaquoddy Spray Project, 1983

Behavior	T4ND BPP			T5ND BPP		
	6/1	6/9	6/15	6/1	6/9	6/15
% Wandering	39	26	53	25	25	51
% In Needles	43	0	0	60	2	0
% In Buds	12	56	37	6	58	40
% Other ^{a/}	6	18	10	9	15	9
	100	100	100	100	100	100

^{a/} Includes larvae webbed either on or near buds or found loose in the bags.

SPRAY EFFICACY EVALUATION

Samples and Sample Clusters

A total of 45 sample clusters were established in 10 treatment blocks. Each cluster was a line of 20 dominant/codominant spruce trees spaced about 50 feet apart, across the anticipated spray swaths.

Additionally, three check blocks were established in widely separated areas at least ½ mile outside the spray blocks. Each check block had four clusters established in a manner similar to the spray blocks. Despite these precautions, Bt deposits were found in two of the three check blocks.

Prespray Survey

Prespray samples consisted of one 18-inch-long branch taken from the midcrown of each sample tree. Collections were made two to three days before spraying. The branches were bagged, labeled and delivered to a laboratory for examination. The average number of larvae per 18-inch branch was determined in the laboratory.

Postspray Survey

Postspray samples included two branches, each 18 inches long, taken from the midcrown of the sample trees. The samples were collected about 40 days after spraying when larval feeding was completed. This coincided with 10 percent adult emergence. Again, branches from each tree were bagged, labeled and delivered to the laboratory. In the laboratory, the average number of budworm per branch and the degree of defoliation were determined from 25 shoots rated in 10-percent defoliation classes.

Spray Deposit Assessment

Spray coverage was evaluated at the sample clusters in nine of the ten treatment areas and in all the check areas. Foliage samples were collected from the midcrown and from the lower crown of each sample tree. In each treatment area, deposit assessment was made for five trees in each of the selected clusters. In addition, millipore filters were exposed on 3 foot stakes near sample trees. In each treatment area, five filters were set out in each cluster. The filters were set out 8 to 12 hours before spraying and picked up within six hours after spraying. Foliage samples were taken as millipore filters were collected.

About a month later, all deposit samples were placed on tripticase soy agar plates and the spray coverage determined. For foliage samples, 20 old needles from each branch were placed on agar. After incubation, the proportion of needles producing Bt colonies were determined. Sample colonies from each dish were examined under a microscope to confirm the presence of Bt crystals. The millipore filters were handled the same way, except that the number of colonies per square centimeter was determined.

Field Laboratory

Foliage examination was done in a laboratory operated by the PFD. Personnel included experienced workers. Branches were brought to the laboratory and kept refrigerated. They were examined within a week after collection.

RESULTS AND DISCUSSION

Efficacy

The average defoliation in treated areas was 23 percent. Spruce budworm populations declined in treated areas from 865 to 62.5 budworms per 100 square feet of foliage. Thus, the average spruce budworm mortality was 94 percent.

The results for each treatment are summarized in Table 4. The differences between treatment means were analyzed using Student's Newman Keuls test ($p = 0.05$). Spruce budworm mortality was significantly higher in undiluted Dipel 6L treated blocks than in undiluted Thuricide 48LV or diluted Thuricide 32LV treated blocks. Although the differences between diluted and undiluted Dipel 6L treated blocks were not significant with the Newman Keuls test, both budworm mortality and defoliation were significantly different based on a grouped t test.

No other treatment means were significantly different. The sampling method used 20 tree lines as clusters and did not give enough samples to detect mean differences of less than 10 percent with normal field variation.

A comparison was made between diluted and undiluted treatments of Dipel 6L and Thuricide 32LV combined. The undiluted treatments had significantly lower defoliation and higher budworm mortality than the diluted treatments (Student's t test, grouped data; $p = 0.05$).

Table 4.--Spruce budworm population changes and spruce defoliation in the Passamaquoddy Spray Project, 1983

Treatment	Rate (fl oz /acre)	Clusters	Deposit % Needles cov'd	Mean No Larvae/ 100 ft ²		% Mortality		% Defol	
				pre ± se	post ± se	± se	± se	± se	± se
Dipel 6L	32	5	32	664 ±81.7	12.4 ± 2.3	98 ± 0.5	20 ± 3.2		
Dipel 6L	32	4	65	935 ± 116	5.6 ± 3.3	99 ± 0.3	13 ± 2.9		
Dipel 6L	65	7	47	1090 ±73.3	14.7 ± 2.3	98 ± 0.4	28 ± 2.9		
Dipel 6L	65	4	50	1412 ±25.5	82.6 ±16.4	93 ± 1.7	25 ± 2.9		
Dipel 6L	65	4	--	918 ± 318	86 ± 7.0	86 ± 4.7	21 ± 2.7		
Dipel 8L	16	3	53	821 ± 137	30 ±12.2	95 ± 2.7	18 ± 0.7		
Thuricide 32LV	48	4	87	921 ±73.5	32.5 ± 7.2	96 ± 0.9	19 ± 4.4		
Thuricide 32LV	64	4	97	972 ± 206	69.1 ±14.0	91 ± 3.5	16 ± 3.1		
Thuricide 32LV	64	4	70	1742 ± 214	87 ± 6.6	95 ± 0.5	24 ± 2.8		
Thuricide 48LV	32	6	43	304 ±50.7	23.5 ± 5.3	88 ± 5.8	17 ± 2.4		
Check 1		4	5	969 ±22.4	115 ±20.2	81 ± 9.3	28 ± 2.9		
Check 2		4	28	314 ± 119	142 ±31.4	57 ±10.3	32 ± 5.6		
Check 3		4	0	471 ± 116	174 ±76.7	50 ±21.1	32 ± 2.9		

Spray Coverage

Spray deposit in the treated areas indicated good coverage (Table 5). No significant differences in deposit were found between midcrown and lower crown needle samples (60.9 percent vs. 59.3 percent of needles with Bt). On millipore filters, the average count was 48.2 colonies per cm². However, one block (47) had an average of 171 colonies per cm², suggesting multiple coverage. Without that block, the average deposit was 32.9 colonies per cm².

Our work with aerial application of Bt over the past three years indicate that checks need to be sampled for Bt deposits. As in the previous years, the current year's checks received some

Bt deposits. Although, the amounts are considerably less than what is found in the sprayed areas, some budworm mortality from Bt is expected, and therefore, the checks do not represent truly untreated Bt areas.

Table 5.--Spray deposit assessment for the Passamaquoddy Spray Project, 1983

Treatment	Rate (fl oz/ac)	Block No	% Needles Producing Colonies		Millipore Filters (Colonies/ cm ²)
			Mid- crown	Lower crown	
Dipel 6L	32	72	36	28	24
		43	59	70	34
Dipel 6L	65	45			
+2%		48	52	48	19
Sticker		71	51	42	15
Dipel 8L	16	49	49	56	90
Thuricide	48	46	88	86	22
32LV					
Thuricide	64	44	96	97	24
32LV + 2%		47	73	66	171
Sticker					
Thuricide	32	73	44	41	45
48LV					

ACKNOWLEDGEMENT

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PENNSYLVANIA'S EXPERIENCES WITH MICROBIAL CONTROL OF THE GYPSY MOTH

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ABSTRACT

Pennsylvania's first experience with using Bt on insect control occurred in 1964. For the next 17 years, various projects were conducted, in cooperation with the USFS and industry, in an effort to secure operational status of Bt for gypsy moth suppression. This point was reached in 1982, and the Governor was convinced that the time was right to convert most gypsy moth suppression operations from chemical spray to Bt. In 1983, 326,000 acres of high-use areas were treated with Bt, making it the largest Bt operation on the gypsy moth undertaken to date. Suppression results were virtually on a par with formerly used chemicals, spraying objector problems dropped to near zero, and the per acre suppression cost was cheaper. Some problems with Bt still remain, and these are discussed.

My remarks in this presentation will be confined to Bt since we have no operational experience with other microbials in gypsy moth suppression. The gypsy moth virus material may at some future date prove to be operationally feasible, but it is my opinion that this is still a long way off. It doesn't match Bt in effectiveness, at least at this time.

Being an old timer with 27 years of responsibility for gypsy moth suppression in Pennsylvania, I cannot help but reflect for a minute on long-term trends. When I first came on board in 1957, DDT was under attack. The hue and cry was to switch to less offensive "soft" chemicals such as carbaryl or trichlorfon. This was finally done in the early 1960's, and for a period of time we had little or no problems with opposition to chemical spray programs. In the 1970's, however, these biodegradable chemicals came under attack. The insistence then was that we switch to Bt.

Two things should be obvious: 1) much energy has been expended uselessly in fighting the long-term and inevitable trend away from broad-spectrum chemicals. This energy should have been expended in accelerating the conversion to microbials, and 2) if you think back to your college days you might remember some professor saying that one of our ultimate goals in forest insect control must be the development and use of specific suppression materials that have little or no impact on other organisms, the environment, and on humans. We have entered this new era of micro-

bial control on a large-scale within just the past two years. Work is now accelerating at a rapid rate, witness the number of new Bt formulations that become registered every year.

In Pennsylvania, I like to think that we have never forgotten our ultimate goals. My first contact with a microbial insecticide was back around 1960, when we made a concoction of virus to use on the European pine sawfly. It worked, but its use was soon halted by EPA.

Our work with Bt began in 1964, when we sprayed several hundred acres to test its control of the fall cankerworm. Results were variable to say the least. Over the next 17 years, our experimental work with Bt was primarily on the gypsy moth. Very few years went by without some Bt spraying, but results always left something to be desired. We could kill gypsy moths, but more than one of us suspected that a 1974 Bt spray operation on 35,000 acres did nothing more than prolong the outbreak, due to the number of healthy survivors. We also had the dubious honor in 1974 of having this large Bt operation temporarily stopped by EPA for possible violation of the terms of an experimental label. This necessitated a trip to EPA headquarters in Washington to straighten the matter out, and it made us wonder who our friends were.

At this point, I would like to pay tribute to a man who has devoted his entire career to the development of microbial insecticides. During these earlier years, he never gave up hope that someday Bt would become a viable replacement for chemical sprays. I'm sure he had many frustrating experiences, but his dedication to the task never left him. He is, of course, Dr. Frank Lewis. I don't know where we would be today with Bt if Dr. Lewis had not been on the job.

In 1981, some outstanding successes began with the newer Bt formulations. In 1982, we decided to conduct a large-scale project with Bt as part of our operational program. This was done on 32,000 acres of forested residential properties in southeastern Pennsylvania. Results were as good as with chemical spraying. Twelve B.I.U.'s were used in 128 ounces of solution per acre. A polyvinyl sticker was used over much of the area but was later abandoned due to its propensity to adhere semi-permanently to automobile finishes. We also augmented the Bt spray areas with *Apanteles* parasites with good results.

Following this successful operation with Bt, we felt the time was right to recommend a major changeover in our program from trichlorfon (Dylox) to Bt, at least in all forested residential areas. Trichlorfon was becoming too expensive, and chemical spray objectors were presenting us with severe operational problems. This recommendation was approved by the Governor who, in fact, directed us to make the changeover.

In 1983, we treated 326,000 acres with Bt, involving over 3,000 separate spray blocks of forested residential properties. Twelve B.I.U.'s

were used over most of the area, with gypsy moth densities of over 1,000 egg masses per acre in building populations receiving 16 B.I.U.'s and in some cases two treatments. The significant results of this project can be described as follows:

1. The spraying objector rate of 5-10% with previously used chemicals dropped to virtually zero with Bt. Environmentalists not only ceased their attacks but applauded the conversion. The mail that did come in was mostly from pest control officials and environmentalists in other states seeking Bt efficacy data and the reasons for our changeover. It was obvious that Pennsylvania's action influenced some other states to chart a similar course.

2. Overall costs were about \$1.00 per acre lower than with previously used chemical sprays.

3. Control results with Bt were generally acceptable, with about 80% of the areas showing 70-93% larval mortality and defoliation below 30%. Overall egg mass reduction was not as good as with chemical sprays. Many areas with building populations still had unacceptable numbers of larvae, resulting in a continuing public nuisance problem. However, even in these latter cases, foliage protection was achieved.

4. In a large program, making two applications 7 to 10 days apart in critical areas presents excessive operational problems, which we must avoid if at all possible. In 1984, we will try 20 BIU's in these critical areas. An alternative for evaluation may be two applications of 12 BIU's on the same day. In general, our treatments with 16 BIU's were not significantly better than the 12 BIU treatments in the limited areas where they could be compared with equal populations. It should be noted that control problems also existed in many of these same critical areas with chemical sprays. Basically this occurs either because foliage is being consumed as fast as it is being produced, leaving little leaf surface to spray, or because later hatching larvae are being blown in a week or more after treatment.

5. Timing of Bt applications did not prove to be as critical as we had feared, but the spring of 1983 was unusual. We allowed ourselves two weeks to get the job done in each of three geographic regions of the state. Due to cool weather after general egg hatching and reduced feeding activity, we had at least three weeks for spraying in each area. In a few areas, poor control was traced to spraying too early. The ideal start time is when white oak foliage is one-third grown.

6. We attempted to evaluate spray stickers but could not come up with any concrete evidence that they improved control. In 1984, we will only use stickers if there is a threat of rain. Our plans also call for retreating an area if rain occurs within 4-6 hours of treatment.

7. Mixing Bt solutions proved to be a headache, primarily due to inadequate equipment by contractors and our need to monitor the mixing. This mixing process, on occasion, resulted in 18 hour work-days. We experienced no significant differences in the two Bt products used, Dipel 6L and Thuricide 32LV, in the matters of efficacy, cost, and ease of spraying.

8. Considerable work was done on solution rates. About three-quarters of the operational program was done with 128 ounces per acre, and the remainder with 96 ounces. No detectable differences in efficacy existed. Consequently, the 1984 program with 12 B.I.U.'s will be 96 ounces per acre. In 20 B.I.U. areas, we will use 128 ounces as insurance for good coverage. In 1983, we also conducted experiments on thirty-four 100 acre plots to test nine Bt formulations in reduced solutions and undiluted rates. Undiluted Bt, for the most part, gave unsatisfactory control, as did solutions under 96 ounces.

To reflect on where we are now with Bt in gypsy moth suppression, there is no doubt we have come a long way. However, we are not at a resting stage; perfection is the name of the game. The way to proceed should be fairly obvious. Ideally, a spray operation should utilize undiluted material in one application. I feel certain that this is within our reach, since there is no doubt that Bt will kill gypsy moths. Expedited research in spray technology must be implemented. For example, we are still using the same spray nozzles that were in use 30 years ago. Do we really know the best type of spray aircraft to use, its speed, its spraying altitude, its swath width, and atmospheric condition limits to achieve the best results? Do we know what kind of Bt coverage we're getting within tree canopies and how long it will be effective? These are the answers we now need.

I am convinced that Bt will be in our gypsy moth suppression operations for a long time. Outsiders may not appreciate the tremendous, time-consuming burden that has been lifted from our backs by not constantly being in battle with the anti-chemical spray groups and answering public concerns for safety of their health.

MICROBIAL CONTROL OF THE GYPSY MOTH IN RECENTLY INFESTED STATES: EXPERIENCES AND EXPECTATIONS

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Experiences and expectations concerning microbial control of the gypsy moth in recently infested states are summarized. Initial experience included mixed results, but expectations remain optimistic. Public sentiment assures continued pressure for improvement in microbial control technology.

In states where the gypsy moth is a recent arrival, experience with microbial control is, of course, limited. But interest and expectations are high. Results of a survey in December, 1983, show that nine of sixteen recently infested states have already used microbials at least once, although only three have ever sustained heavy gypsy moth defoliation (Table 1).

have used Bt where the gypsy moth is a relatively new problem, opinions of its efficacy and reliability range from approbation to deprecation. This divergence corresponds to the diversity of circumstances under which Bt has been applied--from attempts at eradication of incipient infestations to the suppression of outbreak populations.

Perceived environmental impact is a major consideration in gypsy moth suppression programs because of increasing public concern about the hazards of pesticide use. Public perceptions of the materials currently registered for gypsy moth control clearly place microbials in a preferential position, especially in comparison with broad spectrum insecticides. But efficacy, cost and consistency of performance are also important attributes, and the record for microbials in these areas has been erratic. Recent advances in the formulation of Bt, a concomitant reduction in application costs and apparent improvement in performance have maintained optimism about its usefulness; but reservations remain. Concern about efficacy and predictability of performance was mentioned repeatedly in survey responses. Most recently infested states are still dealing with incipient populations,

TABLE I: Gypsy Moth Control In Recently Infested States^{a/}

State	Has had Heavy Defoliation	Control Materials Applied			
		Broad Spectrum	Growth Regulator	Pheromone	Microbial
Arkansas	-	+	-	-	-
Delaware	+	-	+	-	+
Georgia	-	-	-	-	-
Illinois	-	+	-	+	+
Maryland	+	+	+	-	+
Michigan	+	+	+	+	+
Minnesota	-	+	-	-	-
Missouri	-	-	-	-	-
North Carolina	-	+	+	+	+
Ohio	-	+	-	-	-
South Carolina	-	+	-	+	-
Tennessee	-	-	-	-	-
Virginia	-	+	+	+	+
Washington	-	+	-	+	+
West Virginia	-	-	+	-	+
Wisconsin	-	+	-	+	+

^{a/} Responses to a survey in December, 1983; + = yes, - = no.

Most conventional and experimental approaches to gypsy moth control have been used or tested in recently infested states. Microbials, especially *Bacillus thuringiensis* (Bt), are expected to constitute an important component of all future suppression programs. This apparent predilection for Bt reportedly stems more from reaction to public pressure than from absolute preference for its characteristics and performance. Among those who

and the primary objective is gypsy moth mortality, rather than foliage protection or nuisance abatement.

Experience with gypsy moth nucleopolyhedrosis virus (NPV) was reported only from Michigan, Virginia, and Wisconsin. Even in these cases it was used on a very limited scale. In Virginia, a recent test of NPV applied to shade trees from the ground produced

encouraging results. Little consideration has been given to NPV by most states presumably because of its very restricted availability and uncertain performance record.

Microbial control is certain to remain an important issue as the gypsy moth extends its range. Expectations in recently infested states include increased use and improvement of microbial formulations. The prevailing attitude is generally one of optimism.

Some Negative Aspects of Using Bacillus thuringiensis Berliner In Operational Programs Against The Gypsy Moth (Lepidoptera:Lymantriidae)

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Operational programs to suppress gypsy moth populations in residential and recreational areas first began in New Jersey in May of 1980. Bacillus thuringiensis was used on approximately 17,000 acres applied at the dosage rate of 8 B.I.U.'s in one gallon of water per acre. Two treatments approximately one week apart were applied.

The insecticide B.t. was used previous to 1980 in pilot test programs, but because of the high cost of materials and erratic results the Department could not recommend it as the viable alternative to chemical pesticides. However, more recently with improved formulations and lower costs it has become more feasible to utilize B.t. in operational programs.

Despite B.t.'s increased efficacy over earlier formulations, there are still a number of negative aspects to consider when used in operational programs. One of the negative aspects of most concern is the narrow "spray window" available to properly control second and third instar larvae especially if there is a prolonged hatching period. However, even when it is applied when the larvae are the proper size, rainfall and/or prolonged cool weather can reduce its efficacy because of the material washing off foliage and the lack of feeding which occurs by the larvae during cool weather conditions.

Additionally, even though we have reduced the number of applications from two to one per spray season, it still is applied at the rate of approximately one gallon per acre which means more operational hours are necessary to complete the work than the low volume chemical insecticides.

Another negative aspect of major concern is the wide variability in efficacy depending on the health and vigor of the gypsy moth population. Building populations of the gypsy moth, where the egg masses are large and the numbers exceed 1,000 egg masses per acre, are much more

difficult to control with B.t. than declining populations of the pest. Declining populations are found when the insect is under stress due to starvation and disease and egg masses are small. Bacillus thuringiensis tends to be more successful under these conditions. Because of this variability, the New Jersey Department of Agriculture occasionally has to re-spray areas containing high building populations because larval reductions were not sufficient to prevent re-infestation of these areas of the following season. This re-treatment sometimes amounts to nearly 50% of the spray block.

Although insecticide costs are greater for B.t. than for the chemical insecticides, the cost is not the major concern when towns make their selection. The effectiveness of the material seems to be the greater concern to town officials. The reason being is that there are certain notification and legal procedures which must precede the spray operation and if after all these requirements are met, the results are not good in terms of foliage protection and population control, the towns will sometimes switch to the more effective chemical insecticides the following season.

Another negative aspect of the B.t. spray is its slow knock-down ability. Residents in the sprayed area believed that once spraying is done, the larvae should rapidly disappear from the area and no further nuisance should exist. This rarely occurs when B.t. is used and some residents complain that the insecticide is not working.

One minor aspect of the insecticide B.t. that is considered negative is a fact that it is very difficult to see on the foliage. Therefore, if residents believe a skip has occurred, it is difficult to verify because the B.t. is virtually colorless on leaf surfaces.

Evaluating the efficacy of B.t. by the New Jersey Department of Agriculture has been done each season since its introduction in 1980 using tar paper bark flaps and comparing results of larval counts in treated and untreated areas at the same time. The best control of larvae during any one season occurred in 1982 when a 70% average larval reduction in all treated areas was accomplished. The lowest larvae reduction of caterpillars had occurred in 1983 when only 40% reduction in larval numbers were observed. Apparently, the woodlands where B.t. was used in 1983, contained extremely high and healthy populations of the gypsy moth and the results were not as good as in previous years.

Finally, the Department does recognize the fact that stickers can increase the residual life and effectiveness of the B.t. application. However, the stickers that work the best are also the most difficult to remove from car surfaces and does present a negative factor since most of the spraying is done in residential areas. For this reason, the Department has used stickers (Plyac or Nu-Film) which are able to be washed off car finishes more readily.

In conclusion, there are a number of negative aspects of using B.t. sprays in residential areas. However, in general, B.t. does not offer good foliage protection, and therefore, the objective of preventing tree loss in these areas is met. The New Jersey Department of Agriculture will continue to recommend and encourage the use of B.t. in spraying operations. However, we do feel towns should be given the opportunity to select the insecticide in a voluntary program, especially when all the aspects of B.t. are considered.

OVERALL ASPECTS OF B. t. IN FOREST SERVICE COOPERATIVE GYPSY MOTH SUPPRESSION PROJECTS

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Improvements in B. t. performance and cost, coupled with public concerns over human health risks have elevated B. t. to a viable alternative to chemical insecticides. Operational use of B. t. in recent years has demonstrated that while foliage protection can generally be achieved in most situations, gypsy moth population reduction cannot. Efforts are needed to improve B. t. performance in healthy, building gypsy moth populations.

Introduction

Bacillus thuringiensis (B. t.) has had a long and sometimes arduous journey in gaining acceptability and respectability in Forest Service cooperative gypsy moth suppression projects. The insecticide's slow acceptance stemmed not only from its high cost, special operational considerations, and erratic performance demonstrated in early field trials, but perhaps also from the misconception of B. t. as a replacement for chemical insecticides. Today, users realize that B. t. is not appropriate in all situations, and efforts are directed at finding the proper role for the insecticide.

B. t. Use in Cooperative Suppression Projects

The use rate of B. t. in cooperative gypsy moth suppression projects reflects an ebb and flow relationship, with increased or decreased use rates in 1 year directly related to the results of field tests or operational trials the previous year. Some of the earliest operational trials with B. t. in Forest Service cooperative gypsy moth suppression projects occurred in 1973-1975. The number of acres treated with the insecticide were small, and never exceeded 1.5 percent of the total project acreage (Table 1). Although foliage protection was generally acceptable in these trials, State cooperators expressed doubts about the prospect of achieving desired population reduction levels. Problem areas were identified in methods improvement, including application timing, dosage, and number of applications required (USDA 1974). During the next 4 years, 1976-1979, B. t. was not used operationally in cooperative gypsy moth suppression projects (Table 1), although field trials continued.

In 1980, B. t. operational use skyrocketed. The three States participating in cooperative suppression projects that year treated more than

37,000 acres with the insecticide or approximately 46 percent of the total project acreage (Table 1). Unfortunately, the results were dismal in most cases (USDA 1981). Operational use of B. t. dropped considerably in 1981 and 1982 (Table 1) as States directed resources to more economical and efficacious insecticides in wake of the increased gypsy moth activity throughout the Northeast.

Table 1.--B. t. use in Forest Service cooperative gypsy moth suppression projects 1973-1984.

Year	Total acres treated	Acres treated with <u>B. t.</u>	Percent treated with <u>B. t.</u>
1973	173,570	2,570	1.5
1974	252,844	2,305	0.9
1975	48,579	700	1.4
1976	42,270	0	0
1977	96,146	0	0
1978	169,880	0	0
1979	69,887	0	0
1980	81,370	37,663	46.0
1981	350,299	22,436	6.4
1982	726,757	66,470	9.1
1983	598,760	418,434	70.0
1984 <u>a/</u>	543,613	214,010	40.0

a/ Proposed.

A variety of factors returned B. t. a leading role in 1983 suppression projects with applications made to more than 400,000 acres or 70 percent of the total project acreage (Table 1). Current plans in 1984 call for B. t. application to 214,010 acres, representing 40 percent of the total acreage proposed for treatment (Table 1).

The acceptability and almost standard use of B. t. in cooperative gypsy moth suppression projects in recent years can be attributed to the following:

1. Methods improvement.
2. Cost reduction.
3. Public acceptance (and pressure).

Since 1980, rapid advances have been made in the methods improvement area. The introduction of new formulations of B. t. have eased mixing, loading, and application difficulties experienced in the past making B. t. more efficient to use operationally. More than any other improvement, the demonstration of acceptable performance with a single application at higher dose rates has elevated B. t. to a viable, cost effective alternative. Marketplace competition by B. t. manufacturers has also served to drive down material costs.

For example, material and application costs in 1983 cooperative suppression projects were as low as \$5.50 per acre. Bids already received by the West Virginia Department of Agriculture (WVDA) for 1984 project work indicate that material and application costs could be near \$6.00 per acre (personal communication, Alan R. Miller, WVDA). These costs are lower than all of the chemical insecticides except Dimilin.

Public concerns over human health risks have generated a tremendous appeal for the use of B. t. in place of the chemical insecticides. Pressure has been applied to public officials by local citizenry through State legislatures and the courts to ban or severely curtail the use of chemical insecticides. Comment letters received for and published in the current USDA Final Environmental Impact Statement for gypsy moth suppression and eradication projects (USDA 1984) are replete with questions on public health risks, particularly cancer and birth defects. Most of these letters support the use of B. t. instead of chemical insecticides. The recent increase in B. t. use, particularly in populated areas, can be largely attributed to public pressures, and States' responses to address these concerns.

B. t. and Project Objectives

Is B. t. adequately achieving the objectives of cooperative gypsy moth suppression projects? The track record of B. t. in the last several years is mixed. Comments from State cooperators and data in post-suppression evaluation reports indicate that except in extremely high gypsy moth populations, the objective of foliage protection can be achieved. Population reduction, however, is variable.

During the 1983 cooperative suppression projects, 418,434 acres comprising 70 percent of the total project acreage in 7 States were treated with B. t. These treatments were applied to a wide range of gypsy moth population levels (250 to more than several thousand egg masses per acre) in different phases of outbreak (building, static, declining) and provide a good evaluation of B. t. The results of 1983 suppression activities in Maryland, New Jersey, Pennsylvania and West Virginia demonstrate similar trends. Treatments in these four States accounted for 98 percent of all the B. t. used in cooperative suppression projects last year.

Maryland.--The Maryland Department of Agriculture (MDDA) treated 50,242 acres with B. t. in 1983. Foliage protection was achieved; however, approximately 42 percent of the treatment areas Statewide contain gypsy moth populations averaging more than 250 egg masses per acre and qualify for retreatment in 1984. Up to 90 percent of treatment areas which have never sustained defoliation, but contain

building populations, qualify for retreatment in 1984 (personal communication, Robert Tichenor, MDDA).

New Jersey.--The New Jersey Department of Agriculture (NJDA) reported that 5,000 of 11,000 acres treated with B. t. last year need to be retreated in 1984. When B. t. is used in areas containing building gypsy moth populations in excess of 1,000 egg masses per acre, NJDA expects the need to retreat nearly 50 percent of the acreage the following year (personal communication, John Kegg, NJDA).

Pennsylvania.--The Pennsylvania Bureau of Forestry (PA BOF) treated more than 326,000 acres with B. t. in 1983, accounting for 88 percent of their total project acreage. Statewide, 25 percent of the treatment areas qualify for retreatment; however, this ranges from a low of 15 percent to a high of 84 percent. In areas where building gypsy moth populations were present, 44 percent of the treatment areas qualify for retreatment (personal communication, William Slippey, PA BOF).

West Virginia.--The West Virginia Department of Agriculture treated 16,735 acres with B. t. in 1983. These areas had never before sustained gypsy moth defoliation, but contained building gypsy moth populations averaging several hundred egg masses per acre. Foliage protection was achieved, but population reduction was variable, averaging 43 percent overall. In some areas, gypsy moth populations increased more than twice the pretreatment levels. A total of 9,775 acres of the area treated in 1983 (58 percent) may be retreated in 1984 (personal communication, Alan R. Miller, WVDA).

The overall experience with B. t. by State cooperators can be summed up by the conclusions drawn in Pennsylvania's 1983 post-suppression evaluation. In that report, it is stated that "treatments...in healthy-building populations gave inconsistent results. Overall, however, foliage protection was still achieved in the vast majority of areas." Furthermore, "Most treatment areas will not need respraying in 1984, the exceptions being most of those areas which exhibited healthy-building populations." (PA DER 1983).

Planned B. t. use in proposed 1984 cooperative suppression projects will drop to about 40 percent of total project acreage as State users reevaluate the most efficient role for the insecticide (USDA 1984). Pennsylvania, the largest user of B. t. in 1983, plans to treat only 49 percent of project acreage with the insecticide in 1984 while West Virginia's B. t. use will encompass only 16 percent of proposed treatment acreage. B. t. treatments in Maryland and New Jersey will be in between these figures.

It appears that 1984 will be a year of retrenchment as States evaluate new techniques with B. t. in building gypsy moth populations. Pennsylvania, for example, plans to pursue 20 BIU applications in healthy-building populations, and will also gather more operational data on reduced volume applications (96 ounces per acre) and various stickers. New Jersey plans to conduct similar activities. A concerted effort is necessary to continue methods improvement activities in order to improve B. t. performance in these building population situations.

For the foreseeable future, B. t. will continue to be the insecticide of choice in populated areas given the public mood concerning other treatment alternatives. State cooperators agree that single applications of 12 Billion international units (BIU) per acre in static or declining gypsy moth populations do an excellent job and can achieve both foliage protection and population reduction. Where gypsy moth populations are healthy and building, however, B. t. will lose favor unless performance improvements can be demonstrated.

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RECENT FIELD EXPERIENCES WITH BACILLUS

THURINGIENSIS IN CANADA AND RESEARCH NEEDS

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The CANUSA working group on the use of B.t. against the spruce budworm has prepared a document entitled "Guidelines for the operational use of *Bacillus thuringiensis* (B.t.) against the spruce budworm" following six years of extensive cooperative field trials in Canada and the U.S.A. (Morris et al 1984). The document summarized below (Table 1) describes the current state of the art and is based on the consensus of a committee of scientists actively involved in the management of this insect pest in the two countries.

TABLE I. Technical guidelines for the operational use of *Bacillus thuringiensis* against the spruce budworm - summary

1. Potency: Be sure actual potency is as claimed on label.
2. Aircraft: Calibration essential. Use actual tank mix.
3. Mixing sequence: Water then sticker then B.t.
4. Sticker: As recommended by B.t. manufacturer.
5. Dye: None for operational use.
6. Dosage rate: 12 BIU/AC (30 BIU/ha)
7. Volume rate: .25 to 0.5 gpa (2.37 to 4.7 l/ha).
8. Application timing: When buds start to flare.
9. Ground droplet density: Aim for greater than 25 drops/cm².

There are several items in this summary and elsewhere which to my mind requires further study with a view to improving the effectiveness of B.t. I intend to discuss briefly these items, to present some recent field results, and to offer some recommendations for research.

But firstly an update on the operational use of B.t. against the budworm in Canada.

Status of Operation Trials

The summary presented in Table 2 shows quite clearly an increasing use trend between 1979 when the cooperative CANUSA program started and the proposed 1984 use. Between 1979 and 1980, the proportion of forests sprayed with B.t. was very low (1.5 to 2%). The proportion increased to 9% in 1983 and to 14.1% (proposed) in 1984. This represents a substantial increase of B.t. use between the beginning and the end of the co-operative program on the whole, a trend which I expect will continue.

Table 2. Approximate areas (ha) of forest operationally sprayed for spruce budworm control in Canada between 1979 and 1984 (proposed).

Year	Chemical Insecticides	B.t.	% by B.t.
1979 + 1980	4,024,227	83,773	2
1982	2,265,000	34,000	1.5
1983	86,650	7,600	9.0
1984 (Proposed)	2,094,900	343,000	14.1

A summary of the use trend by province (Table 3) shows that Ontario, Nova Scotia and Quebec were the largest users of B.t. between 1979 and 1984 (proposed) based on the percentage of their sprayed areas treated with B.t. New Brunswick also increased their B.t. treated areas but in terms of acreage actually treated with the microbial insecticide the increase was not large. Newfoundland dropped precipitously from 44% in 1979 + 1980 to 1% (proposed) in 1984.

Table 3. Areas (ha) operationally treated by chemical pesticides and B.t. against the spruce budworm in 1979 + 1980 and in 1984.

Province	1979 + 1980		1984 (Proposed)	
	Total	% Bt.	Total	% Bt.
ONT.	49,710	9.5	10,000	80.0
N.B.	3,252,360	0.01	1,930,000	2.1
NFLD.	35,619	43.9	71,300	1.1
N.S.	63,276	47.8	35,000	100
QUE.	791,377	4.2	815,800	32.6
TOTAL	4,191,773	2.0	2,862,100	12.2

Effect of B.t. on budworm biomass

It is generally acknowledged that the non-lethal effects of B.t. treatments are important additional criteria for judging the effectiveness of the microbial agent. This type of effect was recently demonstrated in the field against the budworm in balsam fir stands (Morris and Moore 1983). The data summarized below (Table 4) were gathered from experiments carried out at Riviere du Loup, Quebec in 1981. Note that larval biomass in B.t. treated populations were significantly lower than in the control and the Dipel-vehicle-alone treated populations. There was no difference between the check and the Dipel-vehicle plot. This plus the data on population reductions and defoliations demonstrate that the vehicle had no effect on the population as was suspected by one worker. We also found that the Dipel-vehicle had no demonstrable effect on the incidence of larval and pupal parasitism (Morris 1983).

Table 4. Effect of Thuricide 16B® and Dipel 88® on spruce budworm larval biomass, larval population reduction and defoliation of balsam fir.

Treatments	Larval Biomass (Mg/100 shoots)	% Reduction	% Defol.
Thuricide 20 BIU in 9.4 L/ha	0.86	36a	20±11a
Dipel, 20 BIU in 9.4 L/ha	0.69	36a	21±16a
Dipel vehicle 25%, 9.4 L/ha	44.2	0b	66±16b
Untreated checks	34.2	0b	65±1ab

Potency

Several researchers and operators have received in the past from manufacturers B.t. products which were below labelled potency. Rarely does one have enough time between receipt of the product and the time to apply it to assess labelled potency. This problem, in addition to causing significant errors in experimental applications can create serious credibility gaps between the product user and the manufacturer. I believe some attempt has been made by the

commercial companies to collaborate on the standardization of their product assays but as far as I know there is still no agreement among them. The problem occurred as recently as 1982 when product potencies as determined by suppliers were far in excess of actual potencies as determined by independent laboratories. I want to implore the producers to come to some general agreement among themselves on bioassay technique for monitoring their products. This technique should be one that is fairly easy to use by researchers, independent laboratories, and operators.

I believe that this bioassay problem is due not only to differences in basic technique but also to differences between test insects. Even "minor" genetic differences between and within insect populations may result in differences in their susceptibility to microbial agents. This admittedly makes a standard bioassay procedure rather difficult. One possible way of solving this dilemma is to complement insect bioassay with the enzyme-linked immuno absorbent assay (ELISA) for B.t. endotoxin. The development of this technique while not replacing insect bioassay entirely would be valuable not only for assaying the toxin content of commercial products but also for rapidly assaying tank mixes and field deposits over the short or long term at the ground or tree level. The method is rapid, specific, sensitive and reproducible and I believe, if used, could reduce the variability normally encountered in bioassays. I have no doubt that this has been considered by B.t. and virus producers, so I would be interested to know why it has not been developed to the stage required.

During the 1970's and 1980's, the commercial companies have made a valiant effort to manufacture more highly concentrated B.t. products and have been quite successful in doing so. Products of 48 BIU/US gal. have already been field tested and 64 BIU products are already on the market or will soon be. The obvious advantage to highly concentrated products relates to cost reduction. Much of the cost of earlier materials was due to bulk shipment and this could be reduced by shipping high concentrate products. The other advantage of such high concentrates is the fact that B.t. is most effective when the target trees are densely covered with droplets containing a high concentration of the toxicants.

Table 5 presents data (from Drs. Fast and Sundaram, FPMI) on the relationship between droplet density of B.t. on coniferous foliage and spruce budworm larval mortality. Note that larval mortality at the lowest dosage (8 BIU/ U.S. gal) is highly variable regardless of

coverage. This supports my contention that 8 BIU /acre is only marginally effective for both spruce budworm and gypsy moth control.

However, just 3 drops/needle at 12 BIU/gal gave acceptable mortality. A 12 BIU/acre dosage rate is gaining general acceptance by operators. Thus if B.t. is commercially formulated in concentrated form so that the 12 BIU/acre will allow a high level of atomization (VMD circa 60 μ m), low evaporation rate and dense coverage at the feeding site, then the cost-benefit relationship in forestry applications should be entirely acceptable.

Table 5. Relationship between droplet density on coniferous foliage and spruce budworm larval mortality following aerial application of *Bacillus thuringiensis*^a

Concentration Sprayed	Drops/Needle	% Mortality (50 larvae)
2.1 BIU/l (8 BIU/US gal)	1 3	20 (16-24) 38 (30-46)
	6	31 (8-70)
3.2 BIU/l (12 BIU/US gal)	1 3	55 84
5.3 BIU/l (20 BIU/US gal)	1 3	78 (70-88) 96 (92-100)
	6	100

^aCourtesy of Drs. P. Fast and A. Sundaram (FPMI)

The question of the most appropriate droplet size for maximum effectiveness against the spruce budworm is also unanswered at this point. It would be useful to know what droplet size one could expect with a particular set of formulation, atomizer and weather conditions but we are still in a state of confusion on this score. To illustrate the problem, Table 6 gives the droplet analyses of undiluted Thuricide and Dipel of drops collected on Kromekote cards during aircraft calibration in 1982.

Table 6. Droplet analysis of spray deposits of undiluted Thuricide and Dipel collected on kromekote cards during aircraft calibration^a

Criteria	Thuricide 48B	Dipel 48B	Thuricide 32B	Dipel 32B
Spread Factor				
Mean \pm SE	1.2 \pm 0.09	1.2 \pm 0.01	1.2 \pm 0.09	1.2 \pm 0.08
D _{min} (M)	<25	17	<25	17
D _{max} (M)	233	302	323	417
NMD (M)	50	41	155	163
VMD (M)	100	66	205	207

^aApplied with AU3000 Micronairs

We see that the droplet maximum diameters (D_{max}) of undiluted Dipel 48B and 32B were larger than those of undiluted thuricide 48B and 32B suggesting that the atomization of Thuricide was superior to that of Dipel. Note, however, that the differences between NMD and VMD (which reflect uniformity of the droplet spectrum) were identical for the two products (i.e. 50 μ m) indicating that the atomization of the sprays were in fact similar, in spite of D_{max} differences. This unexpected similarity is a bit of a conundrum but may have something to do with the viscosities of the products. Viscosity will directly affect droplet size range produced during atomization and also affects indirectly droplet size at the impingement site because it affects the rate of evaporation during descent of the droplet. Dipel acts like a typical non-Newtonian fluid. The apparent viscosities of such fluids can be dramatically reduced depending on shear rate. Research is needed with non-Newtonian products to determine the most suitable apparent viscosities for a variety of nozzle types and shear rates. Some has already been done but to my knowledge has not been published. Such information would help to predict drop-size spectra for a variety of spray systems.

Lastly, when 32B and 48B preparations are compared, the difference between NMD and VMD for Dipel 48B is 25 but is 44 for Dipel 32B. The reason for the apparent difference in behavior between 32B and 48B products is not clear to me. Perhaps manufacturing representatives can explain this.

Stickers

In the CANUSA technical guidelines, we recommended that a sticker be used in all presently manufactured B.t. product tank mixes. We could not find enough well documented information on the effectiveness of various stickers for aerial application and on their compatibility with B.t. to make any general recommendation. We were also aware that different types of formulations may require different types of stickers. We therefore, suggested that operators should follow the recommendation of the product manufacturers.

Table 7. Some stickers used in the aerial applications of microbial agents over forests.

Product	Sticker	Conc./US gal.
Thuricide, Dipel	Chevron	2.365-3.785 Ml
	Dupont	
	Spread sticker	2.42 ml
	Biofilm	4.73 ml
NPV	Rhoplex B60A	75.7 ml
	Biofilm	4.73 ml

Table 7 presents some stickers commonly used in aerial applications of microbial agents over forests. None of these have been fully accepted by operators or researchers in terms of their effectiveness. There is evidently an information gap here which B.t. producers in particular would be well advised to explore. Acrylic stickers (e.g. Rhoplex) are now entering the market and they do appear to be superior to older types of stickers in terms of effectiveness. Other acrylics like 5% Bond and 3% Acrylocoat are highly effective under laboratory conditions (Win McLane, Otis Air Base)

Footnote:

NMD = The diameter that divides the number of droplets into two equal groups - 50% of the droplets have a diameter above the NMD and 50% below.

VMD = the droplet size diameter that divides the spray volume into equal parts - 50% of the volume is in droplets below the VMD and 50% above.

when applied with B.t. or NPV against gypsy moth on red oak seedlings. There are, however, several criteria which should be assessed before a sticker is recommended:

1. It must be determined that the sticker does not delay or inhibit the availability of the microbial agent when it is ingested by the target pest. It should be easily degradable in various liquid environments simulating the insect gut contents of a variety of pest species.
2. It should be non-toxic for the microbial agent. Some microbial agents seem to be particularly sensitive to chemical agents. Microsporiadia in my experience is one such group and nematodes another.
3. Its use should not be limited to certain water types or qualities because the operator often has little choice in terms of the water he must use as diluent.
4. Its chemical nature should not be altered significantly under conditions of high shear produced by aircraft spray systems. In 1982, the use of Phoplex in B.t. tank mixes in Canada put out of action our aircraft flow meter and gummed up the spinning disc cage of our Micronairs delaying our first-application by one day under good weather conditions. Since polymers tends to introduce thixotropic properties to a liquid formulation, some knowledge of their effect on viscosity-shear rate would be helpful for producing desired drop-size spectra during aerial application.

In summary, it seems to me essential that the physical, chemical, biological and toxicological properties of stickers should be tailor-made to achieve maximum spray efficiency with microbial insecticides.

Tracer dyes

The CANUSA guidelines recommended that no tracer dyes be used in operational applications, however, if a dye is needed the recommendation of the manufacturer should be followed. Dyes are sometimes called for in semi-operational and often in experimental trials. As far as I know, the commercial suppliers are not fully agreed on an acceptable tracer dye. A large number of dyes have been tested as B.t. tracer, but, as in the case of stickers, very little information exists on their compatibility with microbial agents, their chemical stability following release from the aircraft, the

maintenance of their integrity on the surface of foliage and their environmental acceptability.

Table 8 gives a list of the most commonly used tracer dyes for aerial applications of microbials over forests.

Table 8. Some tracer dyes used in aerial applications of microbial agents over forests.

Product	Dye	Con./US gal
Thuricide, Dipel ^a	Rhodamine B	3.785 g
	Nigrosine	7.57 g
	Brilliant	
	Sulphoflavine	3.785 g
	Erio Acid Red	
Tussock Moth-NPV	X B400	0.095 g
	Rhodamine B	3.785 g
	BSF	3.785 g

^aWater-based

Table 9 presents data on the compatibility of the dyes with B.t. under laboratory conditions (Morris 1980).

Of the 5 dyes shown, only Rhodamine B had any apparent deleterious effect on spore viability but the half-life was so long, that this effect is considered practically insignificant. Rhodamine B, however, has been reported

Table 9. Decay rates of viable spores of Thuricide 16B diluted 1:1 in water and exposed to 0.1% of various tracer dyes for 21 days.

Dye	Decay Constant (R)	1/2 life-days (95% CL)
Thuricide alone	0	-
Rhodamine B	0.036±0.015	19(10-150)
Brilliant Sulpho		
Flavine	0	-
Nigrosine	0	-
Erio Acid Red		
X B400 ^a	0	-

^aNo significant decay for 69 days.

to induce mutations in Salmonella and DNA damage in hamster ovarian cells (Nestmann and Kowbel 1979; Nestman et al 1979) making it suspect environmentally.

I have used successfully Erio Acid Red XB, a red fluorescent dye chemically related to Rhodamine B (4,5 dihydroxy-3-(P-nitro benzyl) azo 12,7 naphthalene disulphonic acid disodium salt. It is not mutagenic for bacteria. Toxicity data from Ciba Geigy indicate rat oral acute toxicity of 5000 mg/kg; 96 hr fish toxicity-LC₅₀, 1000 gm/l; bacterial activity - no inhibition at 300 mg/l.

Table 10 gives data on the toxicity of EAR for spruce budworm larvae using a foliage dipping technique. No significant toxicity to the larvae could be detected even at a concentration 1000x that used in field tank mixes (25 mg/l).

Table 10. Toxicity of Erio Acid Red XB 400 for L₄-L₅ larvae of the spruce budworm; 5 replicates.

Conc. of Dye (g/l)	Pooled No. of larvae	Adjusted % Mortality
0.025	109	0
0.25	106	3.6
2.5	115	0
25.0	103	0
Check	99	-

Table 11 gives data on the bioassay of Thuricide with and without the dye against L₅ larvae. The "needle inoculation" method was used in which known dosages of B.t. were fed to the larvae on balsam fir needles. The dye had no apparent effect on larval mortality. Because this dye is fluorescent, it has been used successfully in detecting very small droplets of B.t. on coniferous foliage under fluorescent optics. It should be tested with other microbial agents.

Sunlight screens

Several workers have demonstrated that B.t. and other entomopathogens are rapidly inactivated by sunlight and some have shown that the residual activity of some of these agents can be enhanced by the addition of

Table 11. Bioassay of Thuricide 16B with and without Erio Acid Red XB400 (0.25 g/l) against 5th instar spruce budworm^a.

Dosage/larva	No.	Adjusted % Mortality	Statistics
3.1 IU	49	49	
3.1 IU + EAR	49	49	$\chi^2=2.026$, IDF
31.0 IU	49	88	
31.0 IU + EAR	49	93	$\chi^2=0.544$, IDF
Check	49	-	

^aSingle needle inoculation method

sunlight-screens to microbial formulations. Nearly all the published reports so far relate to agricultural systems and only a few of them have done their tests under natural sunlight. Most recently Shapiro et al (1983) demonstrated that benzylidene sulfonic acid enhanced the persistence of NPV 3-fold under sunlamps in the 320 to 400 nm range. We designed experiments to find protective materials which could be added to commercial products or to tank mixes intended for aerial application over forests.

Table 12. The effect of sunlight screens on the residual insecticidal activity of Dipel 36B applied to 2 replicate white spruce trees.

Formulation	Slopes ^a	R1/2 in Kcal/ cm ^{2b}	Absorb Max. (nm)
Dipel alone	-0.202a	1.8	270
1% DS49+CYASORB + 0.5% CMC	-0.148ab	2.4	282,320
1%DS49 = 1% UVITEX + 0.5% CMC	-0.087ab	4.1	282,330
DS49 + 0.1% EAR			282,320
+ 6% MOLASSES	-0.069b	5.3	400,565
1% DS49 + 0.1% EAR			
+ 1% PVP + 0.5% CMC	-0.129ab	2.8	282,328 565

^aEstimates followed by the same letter are not significantly different at 5% level (SNK)

^bR1/2 represents the amount of radiation required to reduce the potency by 50%.

The data in Table 12 summarizes the results of experiments designed to test the

effect of sunlight screens on the residual activity of Dipel 36B applied to white spruce trees. Of the four formulations of sunscreens tested, DS49+ EAR+ molasses had the largest number of absorbance peaks within the solar wavelengths, the highest R/2 (the amount of solar radiation measured in KCal/cm² required to reduce the potency of B.t. by 50%) and a slope that was significantly different from that of Dipel without sunlight screens.

This sunscreen formulation was aerially tested against the spruce budworm in balsam fir stands. The results are summarized in Table 13.

Table 13. The effect of the addition of sunlight screens^a to commercial *Bacillus thuringiensis* (Thuricide 32BX) on larval population reduction of and defoliation by the spruce budworm in balsam fir stands.

Dosage rate BIU/ha	% Larval Population Reduction at Days		Percent Defoliation ^b
	Post-application 14	21	
10	0b	9b	69d
10+screen	67a	79a	39ab
20	63a	68a	45bc
20+screen	67a	88a	55cd
Check I	0b	0b	71d
Check II	0b	0b	89d

^a1% Uvinul DS49 (Sodium 2,2'-dihydroxyl-4,4'-dimethoxy-5-sulphobenzophenone) +0.1 Erio Acid Red B 100 (sodium salt of formyl-m-benzenedisulphonic acid).

^bDefoliation values followed by the same letter are not significantly different at 5% level.

In these tests molasses was omitted from the mixture because of the already high sugar content of the Thuricide used.

The results indicate that at the lower dosage rate of B.t. (10 BIU/ha), the effectiveness of Thuricide containing the sunlight screens was significantly greater than that of Thuricide without the screens. The screening effect was apparently masked by the higher level of active ingredient at the 20 BIU/ha application rate. Thus, it may be possible to reduce the dosage rate applied by extending the residual life of the B.t. on forest trees.

In summary, while the effectiveness of currently produced B.t. has improved greatly over that of the older products, greater effort on the part of manufacturers to formulate their products with sunlight screens to enhance residual activity seems fully justified to me.

Table 14. Effect of single vs. double application of the same dosage rate on population density reduction in and defoliation of balsam fir stands.

Treatment	Colonies per cm ²	% Population Reduction ^b	% Defoliation
Dipel 2x10	82	91ab	35a
Dipel 1x20	42	84ab	24a
Thuricide 2x20	71	81ab	35a
Thuricide 1x40	77	95ab	36a
CH-I	--	0c	71b
CH-II	--	0c	89d

^aDipel population density/100 shoots, 23 and 24; Thuricide, 23 and 27.

^bFinal post-spray corrected for pupal mortality. Values followed by the same letter are not significantly different at 5% level (ANOVA, Tukey's).

Single vs. double applications

Double or split applications of B.t. are generally accepted as necessary in mixed stands of white spruce, *Picea glauca* and balsam fir, *Abies balsamea*, but the strategy of applying split applications of B.t. in unmixed stands has been in question. Aerial applications of Dipel and Thuricide in spruce budworm infested balsam fir stands were designed to answer this

question. The results summarized in Table 14 indicate that split applications are not significantly more effective than single ones of the same dosage as measured by defoliation and population reduction (Morris 1984).

Dosage and Volume

The question of the most effective and appropriate dosage and volume for aerial application against the spruce budworm was the subject of a cooperative field research project between Canada and the U.S.A. two years ago. In Canada, doses of 10, 20, 40 and 80 BIU in 9.4 l/ha and 30 BIU in 2.4, 4.7 and 9.4 l/ha were applied against budworm populations ranging in density between 10 and 36 fourth instar larvae per 45 cm branch in balsam fir stands. The results of the dosage test (Table 15) show that while larval population reduction and defoliation were statistically similar between 20 and 40 BIU/ha, considering the acceptable limits of 75% population reduction and 50% defoliation of current year's growth, the 20 BIU/ha treatment was only marginally acceptable. When the values were adjusted for differences in population densities by calculating the ratios of larval density to population reduction and % defoliation, it is apparent that the efficacy of the treatments increased with dosage applied. This supports the recommendation of 30 BIU/ha as being likely to give more consistently acceptable results than 20 BIU/ha.

Results of the tests on volumes (Table 16) indicate that the volumes applied between 2.4 and 9.4 l/ha had no significantly different effect on population reduction and defoliation. In fact only the treatment at 2.4 l/ha gave less than 50% defoliation. These data support the CANUSA recommendation of applying B.t. in volumes between 2.4 and 4.7 l/ha.

Table 15. Population reduction and defoliation in balsam fir stands treated with various doses of Thuricide 32B in 9.4 l/ha.

Dosage BIU/ha	Larval density/45 cm branch	Population reduction (%)		Ratio	
		21 days post-application	Defoliation (%)	Larval density/pop. red.	Larval density/% defol.
Check	14	1 d	80 b	14.0	0.18
10	16	9 cd	69 b	1.8	0.23
20	12	68 ab	45 a	1.8	0.27
40	16	95 a	36 a	1.7	0.44
80	36	95 a	61 b	0.4	0.59

Table 16. Population reduction and defoliation in balsam fir stands treated with various volumes of Thuricide 48B at 30 BIU/ha.

Volume/ha	Larval density/45 cm branch	% population reduction 21 days post-application	% Defoliation	Ratio	
				Larval density/pop. reduction	Larval density/% defoliation
Check	18	75 a	86 a	0.24	0.21
2.4	10	68 a	45 b	0.15	0.22
4.7	17	72 a	59 ab	0.24	0.29
9.4	16	76 a	56 ab	0.21	0.29

^aThree replicates

To summarize this discussion as a whole, I offer the following recommendations:

1. Every effort should be made by B.t. manufacturers to guarantee the potency of their product to the satisfaction of their clients.
2. Manufacturers of B.t. ought to continue their already valiant efforts to formulate their products in highly concentrated form in order to reduce application costs to users.
3. Stickers should be well researched for their effectiveness, bioavailability of microbial agents with which they are mixed and their compatibility with various formulations and spray equipment before they are marketed or recommended.
4. While tracer dyes for B.t. are not generally recommended for operational B.t. sprays, they are sometimes needed for semi-operational and experimental trials. Such dyes should be non-toxic to target insects, to the microbial agents with which they are mixed and should be environmentally acceptable. Erio Acid Red is suggested as an acceptable dye.
5. I recommend that a concerted research effort be put in place by B.t. manufacturers to find effective sunlight screens which can be added to their commercial formulations or to tank mixes.
6. Information on the most effective droplet sizes for spruce budworm control is sparse. More research is needed in this area.

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RECENT FIELD RESEARCH EXPERIENCE WITH B.T.
AGAINST SPRUCE BUDWORM IN THE EASTERN U.S.

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Recent testing in the eastern U. S. has led quickly to the adoption of 12 BIU/acre as the best operational dosage rate, with operational spray emission rates reduced to a quart or less per acre. Some recent work suggests that older larval instars of the budworm are highly susceptible to B.t. sprays, and the effective "spray window" can be broadened when budworm populations are moderate. New studies on second-year benefits of B.t. treatments are producing negative results.

Introduction

Development of B.t. for spruce budworm control has occurred rapidly and dynamically. In only 4 or 5 years B.t. has changed from a little used, expensive material, of questionable reliability, to one which is now perceived to compete favorably with chemical insecticides in quantities used (in some jurisdictions at least), in cost, and in reliability. The improvements in technology, made by the manufacturers of B.t. and tested by cooperating research groups, have rapidly become operational. These operational changes will have been discussed by other speakers, and we need not dwell on them at length.

The principal tests involved:

1. Comparisons of the major, competing formulations of B.t. (Walton and Lewis 1982, Dimond et al. 1981, Reardon et al. 1982, Grimble and Morris 1983, Morris 1981). These found no significant differences in efficacy.
2. Comparisons of three dosage rates and two dilution rates of B.t. sprays (Lewis et al., in press), as well as results of operational testing (Morris 1982), suggested that 12 billion International Units (BIU) per acre of B.t. produced more reliable results than the prevailing 8 BIU dosage, and should become the standard operational dosage. It was also concluded that spray emission rates of one gallon/acre provided no advantage over 0.5 gallon/acre.
3. Tests of applications of undiluted or "neat" B.t. (Dimond 1982) with spray emission rates as low as 1 quart/acre, were highly successful. This was followed by operational usage, with success, in 1983. Undiluted, or similar low-volume applications, are scheduled for wide use in 1984.

4. A combination of laboratory and field tests (Fast and Dimond 1984) suggested that the later larval stages of the budworm, through early sixth instar, are readily killed with B.t. It is no longer necessary to believe that a narrower "spray window" must be used with B.t. than with chemicals. Later applications, aimed at fourth and fifth instars, are likely to provide best results when budworm populations numbers are not unusually high.

5. In cooperation with Normand Dubois of the USDA, Forest Service, we field-tested one of his new strains of B.t., found in the laboratory to be more efficacious against the spruce budworm. Dubois will present these data in his contribution to this Symposium.

Prolonged Benefits of B.T. Treatments

For the balance of this presentation, I will summarize some unpublished information dealing with the question of second-year benefits of B.t. applications, sometimes called "carry-over effects". The latter term is a poor choice since it implies a possible persistence of B.t. organisms in substantial amounts within the budworm population or on the host trees for a year or more.

While some spores apparently can carry over to a second year (Reardon and Haissig 1983, 1984) there is no evidence that these are in sufficient quantities to affect budworm populations. Second year benefits could be explained, however, by the frequent observation that survivors of B.t. treatments often produce undersized, and presumably unhealthy, pupae and moths (Morris and Moore 1983, Smirnoff 1983, Dimond and Spies 1980). It has been suggested that the generation of insects descending from these stunted survivors may have a low survival potential (Morris and Moore 1983, Smirnoff et al. 1974).

Evidence supporting second year benefits of B.t. applications has been circumstantial until recently. Dimond and Spies (1981) noted significantly less defoliation in small, 100 acre plots treated the previous year, than occurred in nearby control plots. They speculated that population reductions due to B.t. treatments were unlikely to have persisted to a second year because of the small sizes of plots and the high dispersive tendencies of both larvae and moths of the budworm (Greenbank et al. 1980); but, they had no counts of budworm numbers in the plots. Morris (1977) noted that over 2 to 3 years after treatment, both defoliation by and oviposition rates of spruce budworm were lower in treated plots than in untreated plots. In neither of the two cases above was it possible to identify any specific cause for these observations.

In further studies in 1981 (Dimond et al., unpublished¹), we sampled budworm populations and damage in operational spray blocks (3,000 - 15,000 acres) treated by the Maine Bureau of Forestry the preceeding year. Seven blocks were selected, which had received satisfactory protection from B.t. applications in 1980, (Millers 1980), along with seven, nearby untreated areas. Samples of early-instar larvae, late-instar larvae, early pupae, and late pupae (= early adult) were collected in all plots. Insects were counted and instars determined. The latter step was to compare developmental rates between treatments. Subsamples of 200 insects from each collection in each block were reared in the laboratory to measure survival rates. Insects dying were examined for presence of entomopathogens. Defoliation rates were also checked on all blocks, using the standard Fettes system (Sanders 1980).

The results of these observations were inconclusive. Sprayed blocks began the season with somewhat higher mean numbers of insects than control stands (Table 1). However, the control stands had slightly higher numbers in the late collections. This suggests lower survival in the treated blocks, however, the differences were small and not statistically significant.

Percent of insects that were dead in collections were always slightly higher in the four treated blocks in the Molunkus area than in controls (Table 2). But, this was not true in the Caribou area. None of the differences were significant.

Percent of insects that died during rearing, for reasons other than emergence of parasitoids (Table 2), showed no significant differences. Causes of death (Table 3) showed a preponderance of microsporidian infections and unidentified deaths. Bacterial, viral, and fungal infections were rare, and B.t. was not recovered. There were no differences between treatments.

Developmental indices² (Table 4) showed treated and untreated populations in the Molunkus area to be equally advanced in the first collection, but sprayed populations were significantly delayed in the three later collections. In the Caribou blocks, development was significantly advanced in the treated blocks in the first collection, but with no difference in subsequent collections. Both cases suggest a statistically

significant retardation of development of the treated populations, however, the differences were very minor, and perhaps of questionable ecological impact.

Pupal weights (Table 5) were different between areas, probably due to different insect densities in the two areas. But, there were no differences between treatments.

Defoliation (Table 6) in 1981 was greater or equal to levels in 1980, and there were no differences between treatment.

These findings were perplexing. Differences between treated and untreated plots were few and very minor in magnitude. If the differences were real, they were too small to explain the differences in defoliation rates seen the year earlier (Dimond and Spies 1981). But, on the other hand, we did not detect differences in defoliation (Table 7) in this series of blocks. We had no data to explain the earlier observations because prolonged benefits of B.t. treatments were not evident in the plots studied.

To further compound perplexity, we had one additional set of data, also taken in 1981. Defoliation observations were made in a series of 100 acre plots, 25 treated and 5 untreated that were sprayed experimentally with B.t. in 1980 (Dimond et al. 1981). These showed the same results (Table 7) that we had seen the year before; protection from defoliation appeared to persist for a second year. It is unfortunate that we had no population data from these small plots. We had chosen to study the large State blocks, believing that events there would be less influenced by redistribution of sprayed and unsprayed populations after treatment.

Similar studies continued in 1981³. Overwintering larvae were collected in April, 1982 in four State operational blocks that had been treated in 1981, and in four nearby untreated sites of similar character. Collections were made by pruning 25 balsam branches, 1 per tree, in each plot and forcing the larvae from hibernation. Larvae were counted as they emerged, and these were reared through to the pupal stage on artificial diet (Grisdale 1970). Plots had been treated with B.t. at 12 BIU/acre, and this was the first time that this dosage had been used operationally in Maine. No further collections were made on these plots because all were retreated with B.t. in 1982. Observations on the reared insects included development rates, survival rates, and pupal weights. Significantly more insects emerged from the untreated branch collections than from the treated branches (Table 8). There were no significant differences in rates of development or survival or in pupal weights.

¹Dimond, J.B., D.G. Boucias, and C.J. Spies, 1981. Prolonged effects of *Bacillus thuringiensis* treatments on spruce budworm: field observations in Maine 1981. Office report. Entomology Department, University of Maine, Orono, 04469, 23 p. Report available from the author.

²A developmental index for a population containing 10% instar 2, 60% instar 3, and 30% instar 4 is calculated as $(10 \times 2) + (60 \times 3) + (30 \times 4) / 100 = 3.2$. A lower value of the d.i. indicates a younger age structure in the population.

³Dimond, J.B. 1983. Final report on a contract to continue studies of prolonged effects of B.t. applications on spruce budworm. Office report, Entomology Department, University of Maine, Orono, 04469, 12 p. Report available from author.

Table 1.--Numbers of spruce budworms collected in 1981 in operational spray blocks treated with B.t. the preceeding year and in unsprayed stands, mean and range (parentheses).

Block	Collection period - insects per 18 inch branch			
	Early larval	Late larval	Early pupal	Late pupal
Molunkus area sprayed	39(27-50) ^a	28(23-34)	15(11-18)	6(2-8)
Molunkus area unsprayed	30(24-37) ^a	30(25-40)	18(14-24)	6(4-10)
Caribou area sprayed	20(11-32) ^b	-- --	12 (9-15)	8(5-10)
Caribou area unsprayed	17(16-18) ^b	-- --	10 (9-11)	8(7-9)

^aMean and range of 4 replicates.

^bMean and range of 3 replicates.

Table 2.--Percentage of spruce budworms that were dead in collections or died during rearing (in parentheses).

Block	Collection period - % of insects			
	Early larval	Late larval	Early pupal	Late pupal
Molunkus area sprayed	10.0(16.8)	6.8(17.0)	3.2(11.8)	12.4(26.2)
Molunkus area unsprayed	9.9(15.1)	3.5(13.1)	3.1(11.3)	7.2(28.0)
Caribou area sprayed	18.3(15.7)	-- --	8.2(22.1)	10.9(2.8)
Caribou area unsprayed	18.8(15.2)	-- --	10.6(22.5)	11.4(1.6)

Table 3.--Results of tissue analyses of dead larvae in collections and those dying during rearing.

Block	Numbers examined	Diagnosis of larvae, %				
		Bacteria	Virus	Microsporidia	Fungus	Unknown
Molunkus area sprayed	235	5	2	43	7	43
Molunkus area unsprayed	180	1	7	43	6	44
Caribou area sprayed	238	2	1	42	3	54
Caribou area unsprayed	168	3	1	49	8	39

Table 4.--Developmental indices of spruce budworm populations in blocks sprayed with B.t. the previous year and in unsprayed stands, mean and range (parentheses).

Block	Collection period			
	Early larval	Late larval	Early pupal	Late pupal
Molunkus area sprayed	3.4(2.9-3.9)	5.1(4.9-5.2) ^a	5.9(5.8-5.9) ^b	7.3(7.1-7.5) ^b
Molunkus area unsprayed	3.3(2.9-3.8)	5.3(5.1-5.4)	6.0(5.9-6.0)	7.6(7.5-7.7)
Caribou area sprayed	4.4(4.3-4.6) ^b	-- --	6.4(6.2-6.4)	7.0(6.9-7.0)
Caribou area unsprayed	3.9(3.8-3.9)	-- --	6.4(6.2-6.6)	7.0(6.9-7.0)

^aSignificant difference, $p < 0.10 > 0.05$

^bSignificant difference, $p < 0.05$

Table 5.--Weights of pupae collected in blocks sprayed the previous year with B.t. and in unsprayed stands, mean and range (parentheses).

Block	Females	Males
Molunkus area sprayed	28.1(27.0-30.3) ^a	14.2(13.8-14.7)
Molunkus area unsprayed	25.5(22.3-27.7)	14.4(13.9-14.8)
Caribou area sprayed	32.3(31.2-32.9)	16.4(16.1-16.8)
Caribou area unsprayed	31.5(30.1-33.6)	16.4(15.8-17.1)

^aEach mean is derived from approximately 200 insects.

Table 6.--Percent defoliation of balsam fir on blocks treated in 1980 with B.t. and in unsprayed stands 1980 and 1981, mean and range (parentheses).

Block	1980	1981
Molunkus area sprayed	43(35-52)	69(55-81)
Molunkus area unsprayed	52(29-73)	71(63-81)
Caribou area sprayed	51(26-89)	79(62-89)
Caribou area unsprayed	86(79-94)	84(82-88)

Table 7.--Percent defoliation on small plots treated in 1980 with B.t. and in unsprayed plots, 1980 and 1981; means of five replicates.

Treatment	1980	1981
Dipel 1 gpa ^d	56 a ^e	27 a
Dipel 1/2 gpa	60 a	27 a
Thuricide 1/2 gpa	64 a, b	38 a, b
Dipel 1/4 gpa	65 a, b	25 a
Thuricide 1 gpa	77 b, c	46 b, c
Untreated	86 c	70 b, c

^dAll treatments at 8 BIU/acre but with different dilution rates.

^eMeans sharing the same letter are not significantly different, $p > 0.05$.

Table 8.--Observations made in 1982 in four operational spray blocks treated the previous year and in four comparable untreated stands, mean and range (parentheses).

Observation	Treated blocks	Untreated blocks
Numbers of larvae emerging from collected branches	175(95-282) ^a	378(274-494)
Days from emergence until pupation - males	21.3(16.8-23.0)	21.3(17.5-24.5)
- females	23.7(19.1-27.2)	23.9(20.6-26.3)
Percent survival of reared larvae	45 (28-56)	36 (31-41)
Weights of surviving pupae - males	42 (37-49)	44 (32-55)
- females	71 (55-87)	69 (49-93)

^aSignificant difference between treatments, $p > 0.05$.

Before drawing any conclusions from these results, one additional study should be reviewed. Reardon and Haissig (1983) studied 1-year post treatment densities of budworms and defoliation levels in a series of small plots in Wisconsin (Reardon et al. 1982). One year after treatment, populations and damage of the budworm were significantly lower in the treated plots than in controls. Populations declined on all plots in 1981, but the amount of decline was uniform among treatments. Development rates, as indicated by the distribution of larval instars in the collections, and pupal weights were not different. They attributed the reduced defoliation in 1981 as reflecting a persisting reduction in insect population, rather than any "carry over" influence of the B.t. treatments.

We have evidence in three cases (Morris 1977, Reardon and Haissig 1983, Table 8 of this report) that population reductions due to B.t. treatments persisted into a second year. This becomes the most credible explanation of reduced defoliation in B.t.-sprayed plots a year after treatment. We also have one case where population reductions did not persist into the next generation (Table 6). Data available on reduction in population survival of spruce budworms in the generation after treatment are largely negative (Tables 2-5, Table 8, Reardon and Haissig 1983) or show only very small differences. On the basis of results to date, there seems little evidence that the offspring of survivors of B.t. treatments are of less than normal vigor or have reduced potential for survival.

If the conclusions above are true, it follows that population reductions due to any agent, biological or chemical, may persist beyond the generation of treatment, and that prolonged benefits of B.t. treatments may not be a unique attribute of B.t. It may be significant that the three cases where population reductions persisted following B.t. treatments (Morris 1977, Reardon and Haissig 1983, Table 8), and two cases where only defoliation benefits have been reported (Dimond and Spies 1980, Table 7), have occurred in areas of declining population trend. Where there was no evidence of prolonged benefits of B.t. (Table 6), population were high or increasing (Table 1). There may be less redistribution of budworm populations, due to dispersal, and less re-invasion of sprayed plots, in declining populations.

There are delayed benefits of B.t. treatments in that survivors may be stunted, leading to lower survival of pupae and lower egg-production of moths. But, it now appears unlikely that any effect continues into the next generation.

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FIELD TESTS WITH A HIGHLY CONCENTRATED *BACILLUS THURINGIENSIS* FORMULA AGAINST SPRUCE BUDWORM, *CHORISTONEURA FUMIFERANA* (CLEM.) (LEPIDOPTERA: TORTRICIDAE)

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Field tests were conducted in 1980, 1981, and 1982 with a new *Bacillus thuringiensis* formula called Futura. Tests were conducted with a Grumman AgCat aircraft on 40 ha forest blocks and with a DC-4G aircraft on larger forested areas. Futura which is able to disperse the required 20×10^9 I.U./ha for spruce budworm control in 2.5 L/ha proved to be physically and bacteriologically stable and easy to mix. Also it assured a deposit of up to 80% emitted volume, a larval mortality in the range of 70 to 90%, and a foliage protection of about 70%. Because of its low-volume dispersion property and other qualities it is a most valuable alternative to chemical insecticides for spruce budworm control.

Introduction

Investigations with *Bacillus thuringiensis* carried out during the past 10 years, have shown that this entomopathogen can be used effectively for the operational control of spruce budworm, *Choristoneura fumiferana* (Clem.) (Lepidoptera: Tortricidae) (Smirnoff 1978, Smirnoff 1979, Smirnoff 1980a). This work led to the development of a compact, efficient, and economical *B. thuringiensis* suspension which could be dispersed at the dosage of 20×10^9 I.U. in a final volume of 2.5 L/ha (Smirnoff 1981). This preparation, called Futura, was tested during calibration tests (Smirnoff 1980b, c) and field tested in 1980, 1981, 1982, and 1983 (Smirnoff *et al.* 1982, Smirnoff and Valéro 1983).

Materials and Methods

All stands were composed of 70% balsam fir, *Abies balsamea* (L.) Mill., with white spruce, *Picea glauca* (Moench) Voss, trembling aspen, *Populus tremuloides* Michx., and white birch, *Betula papyrifera* Marsh., as remaining species. These stands were 55 to 65 years old and considered adequate for the requirements of pulp and paper industries.

The tests were conducted in the Chicoutimi region of Quebec on 40 ha blocks of forest severely infested with spruce budworm. Three blocks (one

each year) of 3 500 ha, were treated by the Quebec Department of Energy and Resources in the Rivière-du-Loup region of Quebec. Three sample plots, consisting of transects with 5 marked trees, one chain apart, were established in each 40 ha block and eight in a nearby untreated area. Nine sample plots were established in the 3 500 ha treated blocks and eight in a nearby untreated area.

Samples were taken from the upper part of the median section of trees. To assess larval mortality, two samples were made before, and four after treatment in each of the sample plots. Post-treatment samples were collected 10 days after spraying, at peak L₆ and again at 90% adult emergence. For determining defoliation, the methods of Fettes (1950) and Dorais and Hardy (1976) were used. Also, assessment of the current year growth mass was carried out. Tree mortality, efficiency of treatment sequences, loss of wood volume, and stand improvement were assessed in 0.04 ha sample plots established in each treated block and in the untreated area.

The 40 ha blocks were treated with a Grumman AgCat aircraft equipped with a boom and nozzle spray system composed of flat fan (T8004) nozzles. The 3 500 ha blocks were done either with a DC-4G or a Super Constellation L-749 aircraft equipped with a boom and nozzle spray system composed of 110 open type nozzles evenly distributed on each boom in 1981 and 1982, and close to fuselage in 1983 to improve deposit. The spray system on both aircrafts had been calibrated extensively to optimize deposit¹/. For the three years the dispersions were carried out from June 3 to 15, temperature varied between 1°C and 14°C, relative humidity between 60 and 100%, and winds were always below 10 km/h.

The method of Smirnoff (1980b, 1982) was used to assess deposit in number of viable spores per square centimetre. This implies distribution of containers with peptonized water at 30 m intervals along a transect perpendicular to flight lines.

Concurrently, biochemical analyses were conducted on residual pupae from blocks treated with *B. thuringiensis* and from the untreated area to determine any residual effect of *B. thuringiensis* on the spruce budworm populations (Smirnoff 1983). Measurements were also made on residual pupae from blocks treated with chemical insecticides to obtain comparative values.

Formulas used:

1.- Futura ²/: 15% *B. thuringiensis* primary powder (80 000 International Units/mg); 44.8% Sorbo (an aqueous 70% sorbitol solution); 33.7% water; 6.5% inert ingredients; and 1/1 600 Chevron sticker.

¹/Smirnoff and Valéro, submitted, Environment Canada, Canadian Forestry Service Res. Notes.

²/Biochem Products, Montchanin, Delaware, USA

Each hectare was sprayed with 1.5 L of the above preparation diluted with 1 L of non-chlorinated water and 1.56 mL of Chevron sticker.

2.- Thuricide 48B ³/₁: 2 parts Thuricide 48B; 1 part non-chlorinated water; and 1/1600 Chevron sticker.

3.- Thuricide 48LV ³/₁: 50 parts Thuricide 48LV; 20 parts Sorbo; 30 parts non-chlorinated water; and 1/1600 Chevron sticker.

Results

Field tests

1980. In 1980 spruce budworm populations in the region of the field station, Chicoutimi, Quebec, were rather low and tests aimed mainly at comparing Futura with the Thuricide + sorbitol formula used at 4.7 L/ha in large field tests. Results revealed that deposit with Futura was good with 348 756 viable spores per square centimetre over a theoretical emission of 445 000 spores per square centimetre meaning that 80% of emitted number of spores were deposited at ground level. Larval mortality was 72.2% and defoliation 7.45%. These figures compared advantageously with results given by the Thuricide + sorbitol formula and were of course much better than those obtained in untreated plots. Futura dispersed well, provoked a suitable larval mortality, and protected foliage sufficiently. The next step was to test it in severely infested stands supporting various degrees of defoliation.

1981. In 1981 three series of field tests were carried out. The first treated 7 x 40 ha plots with Futura at 2.5 L/ha (20×10^9 I.U./ha) using a Grumman AgCat aircraft. The second test treated 895 ha with Futura at 2.35 L/ha (18.8×10^9 I.U./ha) by means of a Super Constellation L-749 aircraft. The third test, carried out simultaneously with the first test as a companion, involved treatments using Thuricide 32B/sorbo/water/chitinase/Chevron (20×10^9 I.U./ha in a final volume of 4.7 L/ha) by means of a Grumman AgCat aircraft. Results are summarized in Table 1. They show that Futura dispersed by the Grumman AgCat was able to yield a good larval mortality and foliage protection. Larval mortality was 72.0% 10 days after treatment dispersed at 2.5 L/ha compared to 70.3% with Thuricide + sorbitol, dispersed at 4.7 L/ha. Defoliation with Futura averaged 44.1%, but some of the blocks were in a desperate situation after several years of severe defoliation. Thuricide + sorbitol yielded a 67.0% defoliation for a stand in an acceptable condition (Table 1).

Dispersion of Futura by means of the Super Constellation aircraft at 2.5 L/ha yielded a 75.0 to 96.9% larval mortality for a pretreatment population averaging 27.5 larvae per 45 cm with a peak at 46.2 larvae per 45 cm (Table 1). Defoliation was 25 to 40% in plots with 10 to 20 larvae per 45 cm and 50 to 60% in plots with 25 to 35 larvae per 45 cm.

Finally, foliage potential (buds formed in the fall) increased in all treated plots and decreased in untreated plots (Table 1). At the end of the 1981 field season it was concluded that Futura was able to kill spruce budworm and protect foliage with half of the volume of the *B. thuringiensis* formulas used precedingly, 2.5 L/ha instead of 4.7 L/ha.

1982. Five 40 ha blocks were treated with Futura (20×10^9 I.U. in 2.5 L/ha); one 40 ha block with Thuricide 48B (20×10^9 I.U. in 2.5 L/ha); another 40 ha block with Futura (30×10^9 I.U. in 3.75 L/ha); and one more with Thuricide 48LV (30×10^9 I.U. in 4.7 L/ha). The aim was to determine the efficiency of Futura in different conditions of stand deterioration and population levels and compared it with a higher dosage of an other formula. Results are summarized in Table 2. Also, a 3 500 ha block was treated with Futura by means of a DC-4G aircraft.

The number of *B. thuringiensis* viable spores initially emitted was 445 000 per square centimetre for a dosage of 20×10^9 I.U./ha and 667 500 per square centimetre for a dosage of 30×10^9 I.U./ha. In blocks treated with Futura at 2.5 L/ha for a dosage of 20×10^9 I.U., the number of viable spores deposited varied from 269 830 to 406 821 spores per square centimetre and averaged 351 848 per square centimetre. Deposit was 268 862 spores per square centimetre with Thuricide 48B. In blocks treated with a dosage of 30×10^9 I.U./ha, deposit was 520 300 viable spores per square centimetre for Futura (3.75 L/ha) and for Thuricide 48LV (4.7 L/ha), 608 388 spores per square centimetre. Deposit with Futura dispersed with a DC-4G was 222 400 viable spores per square centimetre (Table 2). Deposit varied from 60 to 90% of the emitted number of spores during treatment with the Grumman AgCat aircraft.

Larval mortality established 10 days after treatment averaged 91.5% in blocks treated at 20×10^9 I.U./ha compared with 95.3% in blocks treated at 30×10^9 I.U./ha showing that higher dosage has little effect on spruce budworm mortality. Defoliation of current year shoots averaged 13.4% in blocks treated at 20×10^9 I.U./ha and was 24.7% in blocks treated at 30×10^9 I.U./ha. In untreated areas defoliation was 100% (Table 2).

The current year growth mass also indicates the valuable protection resulting from the use of Futura at 20×10^9 I.U./ha. For each 100 cm branch, 49.0 g of current year shoots were protected while only 1.2 g remained in untreated plots (Table 2). Results using the DC-4G were satisfactory (Table 2). Also, calibration tests conducted in the fall of 1982 with the DC-4G aircraft revealed that an increase of 50% in deposit of *B. thuringiensis* can be obtained by distributing the 110 nozzles on the DC-4G close to fuselage, 55 on each side.*

³/ Zoecon Inc., a subsidiary of Sandoz Inc., Palo Alto, California, USA

*/Smirnoff and Valéro, submitted Environment Canada, Canadian Forestry Service, Bi-Mon. Res. Notes.

Table 1. Results of field tests with *Bacillus thuringiensis* against the spruce budworm in 1981

Formulas	Dosages x 10 ⁹ I.U./ha	Volume L/ha	Deposit viable spores/ cm ²	Pretreatment Populations		Current year growth defoliation %	Mass of current year growth/100 cm branch g	Buds formed (for the next year) %
				Larvae/ 45 cm branch tip	Larvae/ bud			
Grumman AgCat								
Futura	20.0	2.5	283 000	24.9	—	34.7	26.5	93.3
Futura	20.0	2.5	342 850	30.1	—	58.8	17.1	84.5
Futura	20.0	2.5	381 600	17.2	—	38.9	18.6	70.5
Average-Futura	20.0	2.5	335 816	24.0	—	44.1	20.7	82.8
Thuricide 32B/ Sorbo/water	20.0	4.7	413 000	22.2	—	67.0	17.3	85.9
<u>a/</u> Untreated	—	—	—	25.2	—	96.4	4.8	39.4
Super constellation L-749								
<u>b/</u> Futura	18.8	2.35	295 000	10-20	—	25-40	15.1	76.9
<u>c/</u> Untreated	—	—	—	29.5	—	98.7	0.7	6.6

a/ Average for 8 sample plots; b/ Average for 9 sample plots; c/ Average for 5 sample plots.

Table 2. Results of field tests with *Bacillus thuringiensis* against the spruce budworm in 1982

Formulas	Dosages x 10 ⁹ I.U./ha	Volume L/ha	Deposit viable spores/ cm ²	Pretreatment Populations		Current year growth defoliation %	Mass of current year growth/100 cm branch g	Buds formed (for the next year) %
				Larvae/ 45 cm branch tip	Larvae/ bud			
Grumman AgCat								
Futura	20.0	2.5	336 380	28.0	0.14	21.9	33.4	77.8
Futura	20.0	2.5	384 780	17.3	0.13	12.5	46.6	77.9
Futura	20.0	2.5	269 830	20.2	0.19	19.6	42.9	77.8
Futura	20.0	2.5	406 821	24.8	0.37	12.9	67.4	81.1
Futura	20.0	2.5	361 427	12.2	0.13	10.3	54.7	85.3
Average-Futura	—	—	351 848	20.5	0.19	13.4	49.0	79.9
Thuricide 48B	20.0	2.5	268 862	11.8	0.09	8.8	67.4	68.4
Futura	30.0	3.75	520 300	22.7	0.26	22.7	41.2	91.1
Thuricide 48LV	30.0	4.7	608 388	36.8	0.24	26.7	48.3	84.1
<u>a/</u> Untreated	—	—	—	25.7	0.24	100.0	1.2	4.6
DC-4G: Four engines								
<u>b/</u> Futura	20.0	2.55	222 400	31.8	0.19	24.9	43.7	80.1
<u>c/</u> Untreated	—	—	—	30.1	0.28	100.0	0.6	10.2

a/ Average for 8 sample plots; b/ Average for 9 sample plots; c/ Average for 5 sample plots.

1983. The field tests were aimed at determining the theoretical minimum dosage that can be used with Futura. Thus, Futura was dispersed at 2.50, 2.14, 1.43, and 0.71 L/ha (35.0, 30.0, 20.0, and 10.0 ounces/acre). Also, a new device called "pyramid" was developed to determine spreading of *B. thuringiensis* dispersion in a tree for each dosage tested and for each flight. Petri dishes with nutrient agar medium and containers with peptonized water were placed at different levels and depth in the tree crown and under it. Some 2 000 analyses were carried out and preliminary results reveal: there is no relation between the number of viable spores per square centimetre and the number of droplets per square centimetre; evaluation of the number of viable spores dispersed is the only valuable figure for deposit assessment; deposit at different levels in the tree varied with height of dispersion (flight altitude).

Results of field tests are just being analysed and some of them are reported in Table 3. It can only be said at this time that it seems possible to reduce the volume of Futura provided that purer *B. thuringiensis* concentrates be obtained, i.e. concentrates with less inert material. This would permit droplets with a larger number of spores, but still provide the 20×10^9 I.U./ha required for spruce budworm control.

Also, a 3 500 ha block was treated with Futura at 2.5 L/ha by means of a DC-4G aircraft. Although pretreatment population was high, 50.6 larvae per 45 cm or 0.31 larvae per bud, larval mortality was 94.1%, treatment efficiency (Abbott 1925) 78.9%, and defoliation between 40-50%.

Results of Long-Term Studies

Observations carried out during the last 5 years in blocks treated with different treatment sequences, in the *B. thuringiensis* treated blocks, and in the untreated area, revealed an average of 255 dead trees per hectare in treated blocks and 706 dead trees per hectare in the untreated area. Thus *B. thuringiensis* treatments saved 451 stems per hectare. Tree mortality in treated blocks was 12% and it was 40% in the untreated area. This represents the protection of some 29 metric tons of foliage per hectare (12.91 tons per acre) over a 5 year period. Studies continue to determine protection in terms of volume of wood per hectare.

Results of the biochemical analyses conducted during the past 8 years revealed that residual pupae of *C. fumiferana* surviving in *B. thuringiensis* treated areas have greatly reduced potential activity compared with that of pupae from untreated areas, as shown by their weight, calcium level, and total protein content as well as by their hydroxybutyrate dehydrogenase (α HBDH) and phosphatase activities. *B. thuringiensis* has a residual effect on the surviving *C. fumiferana* populations, involving a marked decline in the energy potential which is seen in practice as a reduction in the reproduction ability of the residual pest population (Smirnov 1976, 1983). Conversely, the weights of calcium and total proteins of pupae from areas treated with Fenitrothion (organophosphate) are higher than in untreated pupae. Because α HBDH is of great importance during metamorphosis and adult development, this higher level is significant. It thus appears that the organophosphate treatments encourage the survival of a

Table 3. Results of field tests with *Bacillus thuringiensis* against the spruce budworm in 1983

Formulas	Dosages $\times 10^9$ I.U./ha	Volume L/ha	Deposit viable spores/ cm^2	Pretreatment Populations		Current year growth defoliation %	Mass of current year growth/100 cm branch g	Buds formed (for the next year) %
				Larvae/ 45 cm branch tip	Larvae/ bud			
Grumman AgCat								
Futura	20.0	2.50	349 841	12.3	0.08	32.8	36.0	84.2
Futura	17.0	2.14	142 000	21.1	0.24	55.9	18.6	78.5
Futura	16.3	1.43	143 456	19.9	0.19	54.8	12.4	73.4
Futura	8.0	0.71	135 475	18.8	0.19	49.8	22.1	79.7
a/								
Untreated	—	—	—	20.9	0.28	93.1	2.7	33.2

a/ Average for 8 sample plots.

vigorous C. fumiferana residual population with a high potential activity; in addition, such treatments ensures that more foliage is available for the survivors the following year. Moreover, the emergence of very vigorous populations of C. fumiferana could contribute to the formation of permanent spruce budworm epidemics in areas repeatedly treated with chemical insecticides, as suggested by the epidemiological studies conducted by Blais (1974).

Discussion and Conclusion

The results showed that the high concentrated and low volume B. thuringiensis formula which provides a dispersion of 20×10^9 I.U. in a final volume of 2.5 L/ha, assures good control of C. fumiferana populations and adequate foliage protection. The low-volume required, 2.5 L/ha, meets objectives imposed on cost of material and treatment, because this suspension can be successfully dispersed by means of large capacity aircrafts. Futura formula requires little mixing at the airport, is transported in a concentrated form, and dispersed in a final volume lower than that of the twice yearly dispersions of chemical insecticides presently used against spruce budworm. The conservative sorbitol allows storage of the ready to use Futura, including water, for several months on field sites. Sorbitol is a technical sugar and its osmotic pressure is higher than that of bacterial spores preventing fermentation and contamination. Under laboratory conditions, sorbitol keeps Futura's physical properties at a temperature of 22° C for several months. In 1983, Futura was dispersed in flight temperatures as low as -7° C and results showed that its physical properties were not affected under these field conditions. Also, B. thuringiensis should no longer be considered as a possible way of budworm control, but as an operational method with the same "ready to use" property as all other insecticides presently used against spruce budworm. An efficient control of C. fumiferana can be obtained with 20×10^9 I.U./ha. Therefore why use 30×10^9 I.U./ha (10×10^9 I.U. more) to obtain 10.4% less protection? Is it not a costly waste of material? This was confirmed by B. thuringiensis core tests conducted within ANUSA. These tests also showed that dispersion of B. thuringiensis at 30×10^9 I.U./ha is not more efficient than that of 20×10^9 I.U./ha (F.B. Lewis, personal communication). B. thuringiensis will be used by foresters for the operational control of C. fumiferana if its use remains operationally and economically valid and realistic. As with any method of control, the successful use of B. thuringiensis relies on the strict respect of technological recommendations (Smirnoff 1980d), which means use of the recommended formulas, doses, final volume per hectare, and proper calibration of the spray system of the aircraft.

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Abstract

Aerial spray trials with a variety of viruses have been conducted between 1971 and 1983 with 656 ha (65 plots) treated to control spruce budworm in Ontario and Quebec and 424 ha (6 plots) treated to control western spruce budworm in British Columbia. Generally, results have been inconsistent and less than satisfactory, but research continues in an effort to develop a viral insecticide for spruce budworm population regulation.

Introduction

Four different types of insect viruses have been isolated from *Choristoneura* spp.; nuclear polyhedrosis viruses (NPV), granulosis viruses (GV), cytoplasmic polyhedrosis viruses (CPV) and entomopoxviruses (EPV). NPVs and GVs are classified as Baculoviruses subgroup A and subgroup B, respectively. All these viruses share one common feature, the virus particles are occluded within proteinaceous bodies. When ingested by the insect host larva, the protein is solubilized in the alkaline gut juices, virus particles are released, penetrate the midgut cells and the infection process is initiated. Viruses isolated from various *Choristoneura* spp. are listed in Table 1. Generally, it has been found that they are cross-infectious within the genus, although all the permutations of cross-infectivity tests have not been conducted.

Some of these isolates may contain one and the same virus, but, to date, ones which have been analysed biochemically and compared are all distinct. Restriction endonuclease enzyme (REN) fragment patterns of *C. fumiferana* and *C. occidentalis* NPVs showed they were distinct, but closely related and *C. murinana* NPV was more distantly related (Rohrmann *et al.*, 1982). The inclusion body proteins (polyhedrins) of these three viruses and *C. diversana* NPV were indistinguishable when analysed by peptide mapping and polyacrylamide gel electrophoresis (PAGE), but, using the same techniques, the patterns of the virus particle proteins were all distinguishable (B.M. Arif, personal communication). *C. fumiferana* EPV and *C. conflictana* EPV were virtually indistinguishable when

analysed by PAGE, but were closely related although distinct using REN. *C. fumiferana* and *C. biennis* EPVs were distinct when analysed by PAGE (B.M. Arif, personal communication).

Table 1: Viruses isolated from *Choristoneura* spp.

SPECIES	VIRUS			
	NPV	GV	CPV	EPV
<i>C. biennis</i>				X
<i>C. conflictana</i>				X
<i>C. diversana</i>	X			X
<i>C. fumiferana</i>	X	X	X	X
<i>C. murinana</i>	X	X		
<i>C. occidentalis</i>	X	X		
<i>C. pinus pinus</i>	X			
<i>C. retiniana</i>		X		
<i>C. rosaceana</i>	X			

The most intensively studied of these budworm viruses is *C. fumiferana* NPV and considerable progress has been made in constructing a physical map of the viral genome (Arif and Doerfler, 1983, 1984). This virus has also undergone extensive safety testing in mammals and birds and no ill effects were observed (Valli *et al.*, 1976). If *C. fumiferana* NPV is ever deemed to be an effective and economical alternative to chemical pesticides for spruce budworm population regulation, little additional research is required to prepare a petition for its registration in Canada.

Naturally occurring virus epizootics have never been observed to date in budworm populations although viruses are quite common at very low levels usually with less than 5% of the population infected (Cunningham, unpublished). Initiating and maintaining a virus epizootic in a budworm population is, therefore, a considerably greater challenge than doing so in populations of such insects as gypsy moth, *Lymantria dispar*, and Douglas-fir tussock moth, *Orgyia pseudotsugata*, which are often decimated by naturally occurring NPV epizootics. Spraying these species with NPV advances the time of a population collapse, thereby reducing defoliation and tree mortality.

Since 1971, NPV, GV, CPV and EPV have all been tested in aerial spray trials either alone or in various combinations. Combinations were not tested by choice, but because contamination with a second, or even another two viruses, occurred during virus production. With rigid quality control procedures, this problem has almost been eliminated, although contamination of our NPV product with CPV continues to be an intermittent occurrence.

Field trials have been conducted with viruses to regulate populations of both spruce budworm *C. fumiferana*, and western spruce budworm, *C. occidentalis*, and such parameters as dosage, timing of application, tank mix and adjuvants, spray equipment, droplet size, impact on different species of host trees and persistence of viruses from year to year have been studied. The life cycles and behavior of both species make them difficult candidates for regulation with viruses. Larvae are virtually

hidden until budflush, by which time they have reached the fourth instar or larger. Smaller instars are more susceptible to virus infection than larger ones; also viruses are relatively slow to kill the host and when larger instars are infected only those which ingest a lethal dose of the actual spray deposit will die. There is no time for secondary infection to occur before the onset of pupation. Secondary infection occurs when larvae die from viral infections, disintegrate and release more infectious inclusion bodies on to the foliage. Sprayed at budflush, viruses are really being used as slow stomach poisons, no epizootic occurs in the year of application and little or no foliage is saved.

It was hoped that, following an application at budflush, a sufficient number of dead larvae would remain overwinter on the foliage to serve as a source of inoculum and initiate a virus epizootic in the next generation. Virus does persist from one year to the next, but subsequent incidence of virus infection has never been spectacular and, at present, this cannot be considered a viable pest management strategy. Budworm larvae make little or no contact with each other unless populations are extremely dense. This situation is not conducive to the transmission of a pathogen.

Application of viruses on second instar larvae, as they emerge from hibernacula, is an attractive concept. These tiny larvae are highly susceptible to virus infection, there is ample time for secondary infection to occur and, if there is a hardwood overstory, leaves have not flushed at this time of year and a good spray deposit on conifers can be obtained. However, timing is critical and there are numerous logistical constraints such as freezing temperatures, snow in the forest and impassable, unpaved roads.

Virus Production

Viruses only grow in living cells, so it is necessary to propagate them either in susceptible insect larvae or susceptible cell cultures. *C. fumiferana* NPV can be grown in cell culture (Arif *et al.*, 1976), but, at present, it is not economically feasible to produce in cell cultures the quantities required for field trials. Hence, insect larvae are used.

C. fumiferana was originally selected as the host for production of EPV, NPV and GV, but in recent years *C. occidentalis* has been used as the host for production of NPV and GV; it is more susceptible to infection with both viruses than *C. fumiferana*; less inoculum is required, there is less loss to pupation and *C. occidentalis* larvae spin less silk webbing facilitating faster harvest of dead and heavily infected larvae.

Budworm larvae are small and not ideal hosts for virus production. A mature, NPV-infected sixth instar larva yields 5×10^8 polyhedral inclusion bodies (PIB) and this yield drops on a production line basis. Virus production is labour intensive

and, therefore, expensive. A search has been made for a larger host larva for production of budworm viruses. Intensive efforts to use saltmarsh caterpillar, *Estigmene acrea*, for this purpose were unsuccessful (Shapiro *et al.*, 1982) and although *C. fumiferana* NPV infects neonate cabbage looper, *Trichoplusia ni*, larvae and wax moth, *Galleria mellonella*, larvae, it does not infect large larvae required for virus production (Stairs *et al.*, 1981). The search for an alternative host continues.

Budworm viruses which are currently being produced in *C. occidentalis* larvae are *C. fumiferana* NPV and *C. occidentalis* GV. Large fifth and early sixth instar larvae are placed on artificial diet which has been sprayed on the surface with virus inoculum. When NPV is used, dead and heavily infected larvae are harvested in 10 days and, with GV, harvest time is 12 days at 22°C and 50% RH. Dead and diseased larvae are frozen, lyophilized and ground to a fine powder by mixing lyophilized material with an equal weight of dry ice and processing it in a Waring blender. Batches of material are tested to determine the number of inclusion bodies per gram. Our NPV product, which is currently being produced, contains 10^{10} PIB/g and our GV product 8×10^{12} capsules/g. A count is made of the total number of aerobic bacteria per gram and a check is made for the presence of mammalian pathogens. This is done by culturing in selective media and by intraperitoneal injection of samples into mice.

Spruce Budworm

The first field trials with spruce budworm viruses were conducted in Ontario in 1959 and 1960 when small trees were sprayed with NPV and GV (Stairs and Bird, 1962). In 1969, a range of dosages of NPV was applied on individual small trees at 2 to 3 day intervals throughout the larval period (Bird and McPhee, 1970). In 1970, an EPV isolated from 2-year cycle spruce budworm, *C. biennis* (Bird *et al.*, 1971), although slow acting, was found to give high levels of mortality in the laboratory at much lower dosages than viruses tested previously. It was thought that the EPV would prove to be a highly effective biocontrol agent and the first aerial spray trials were conducted with EPV in 1971 (Bird *et al.*, 1972). Since then aerial spray trials have been conducted almost every year and a total of 65 plots with a combined area of 2 656 ha have been treated with viruses or chemical insecticide/virus combinations in Ontario and Quebec between 1971 and 1983. A list of these treatments is given in Table 2 and a summary of treatments between 1971 and 1980 and their impacts are described by Cunningham and Howse (in press).

The following methods have been used to assess treatments; (a) deposit was monitored on Kromekote® cards, (b) prespray and pupal counts were made from samples from treated and check plots and population reduction due to treatment calculated using a modified Abbott's formula (Abbott, 1925),

c) incidence of virus infection was determined either by microscopic examination of samples of arvae from the field or by rearing collections of arvae and examining those which died, (d) adult emergence on treated and check plots was compared and (e) defoliation estimates were made. Follow-up studies were conducted in most of the trials to determine the impact of the virus treatment in the year or years following the year of application.

Table 2: Spray trials with viruses on spruce budworm in Eastern Canada.

YEAR	TREATMENT	NO. OF PLOTS	TOTAL AREA (HA)
1971	EPV (+NPV+CPV) ^a	6	6.5
1971	NPV (+CPV)	2	4.6
1972	EPV	3	508
1972	NPV	3	268
1972	Fenitrothion/ EPV (+NPV)	1	16
1972	EPV (+NPV)	1	16
1972	Fenitrothion/ NPV	1	16
1973	NPV	9	295
1974	NPV	2	526
1975	NPV	5	318
1976	NPV	3	120
1977	NPV	5	108
1978	NPV	7	134
1979	NPV (+CPV)	6	74
1979	GV	1	6
1979	Orthene/NPV	1	40
1980	GV	1	10
1980	NPV (+CPV)	3	42
1981	NPV	3	108
1983	NPV	2	40
Totals		65	2,656

^aViruses in brackets are contaminants in the material applied.

In 1971, the EPV which was applied was found to be contaminated with low levels of both NPV and CPV and the NPV applied was contaminated with CPV. In 1972, pure EPV was applied, but also in this year, it was found that carry-over of NPV from one year to the next was much better than with EPV, and further trials with EPV were suspended. From 1973 to the present, all efforts have concentrated on developing an effective strategy for the use of NPV and only two small plots have been sprayed with GV.

Dosages of NPV have ranged from 2.5×10^{10} PIB/ha to a double treatment with a first application of 3.4×10^{12} followed by a second application of 2.3×10^{12} PIB/ha. The most commonly used dosage has been 7.5×10^{11} which, on some occasions, has given acceptable levels of population reduction (Cunningham and Howse, in press). When populations are monitored on both white spruce and balsam fir hosts, generally better results are obtained on white spruce. A variety of tank mixes and stickers has been used. Until recently, most were aqueous

and contained 25% v/v molasses, but in the last two years an emulsifiable oil (Dipel 88[®] blank carrier vehicle) has been used, with the virus applied in 25% oil and 75% water. Emitted volumes have ranged from 4.5 to 28.2 L/ha, but most applications were made at 9.4 L/ha. Both boom and nozzle and Micronair[®] rotary atomizers have been used. Generally, coarse droplets with a stain diameter of 200 to 400 μ m have given better results than droplets with a diameter less than 100 μ m. This is a very important point which should be clarified before further applications are contemplated.

Reference has already been made to timing of application and most sprays have been applied at budflush when larvae were in the fourth and fifth instars and sometimes even some sixth instar were present. Results from ground spray applications of heavy dosages of NPV on individual trees at, or prior to, second instar emergence have demonstrated that secondary infection can occur (Bird and McPhee, 1970; W.J. Kaupp, personal communication). Four attempts have been made to aerially spray second instar larvae as they emerge from hibernacula and only one was considered to be timed correctly. Our experience in Ontario, near Sault Ste. Marie, has been that weather generally stays warm in late April and that emergence is over a two to three day period; when the first larvae are observed, it is time to spray and the problem has been applying the spray too late, after larvae have mined into needles and buds. In 1983, in Gaspé, Quebec, weather was cool and larvae emerged slowly over a prolonged period. When larvae were observed on the foliage, NPV was applied, but it remained cool after the treatment and results were disappointing (Cadogan, Kaupp and Cunningham, unpublished).

Carry-over of virus from one year to the next has been monitored in most plots. Following application of NPV contaminated with CPV on two isolated stands of mature white spruce in 1971, levels of virus infection were monitored until 1977 (Cunningham *et al.*, 1975; Cunningham and Howse, unpublished). In the year of application, maximum levels of 21% NPV infection and 28% CPV infection were found in weekly samples of larvae from one plot and 46% NPV infection and 35% CPV infection from the second. Population reductions due to treatment were 69 and 80% respectively, but there was no detectable saving of foliage in either plot. In subsequent years, levels of CPV declined; it disappeared from one plot in 1973 and from the other in 1975. Microscopically detectable maximum levels of NPV in weekly samples of larvae from the first plot each season between 1972 and 1977 were 28, 17, 6, 21, 8 and 3% and from the second plot were 24, 14, 6, 9, 0 and 2%. By 1977, the spruce budworm population had declined to a very low level. Although not spectacular, the NPV had a considerable impact on the spruce budworm population over this period, reinvasion of these isolated stands did not occur and the virus probably exerted sufficient control of spruce budworm to reduce defoliation and thereby prevent tree mortality. Subsequent efforts to repeat this experiment and duplicate these results have proved unsuccessful to date.

The problem of CPV contamination of NPV stocks was solved between 1973 and 1978, but returned in 1979 and 1980. Several interesting observations were made on this contaminated material. Firstly, the levels of CPV contamination have been low and the ratio of NPV:CPV PIBs ranged from 178 to 400:1 (W.J. Kaupp, personal communication). In spite of the low levels of CPV, the incidence of CPV was usually greater than NPV when freshly produced material was applied in the field. When lyophilized, CPV contaminated material is stored for more than one year, the CPV virtually loses all activity and is barely detectable after application of the NPV.

Two small trials were conducted with GV; in 1979, a 6 ha plot was sprayed with 2×10^{14} capsules/ha when larvae were in the fifth and sixth instars and, in 1980, a 10 ha plot was sprayed with 6.4×10^{13} capsules/ha when larvae were in the second instar. Results were inconsistent and there was no relationship between population reduction due to treatment and foliage protection (Cunningham and Howse, in press).

There has been considerable interest in using combinations of chemical insecticides and various pathogens as integrated pest management strategies and this topic has recently been reviewed by Jaques and Morris (1981). Two attempts have been made to use this strategy for spruce budworm control. In 1972, the following treatments were compared: a low dosage of fenitrothion (18g AI/ha) alone, NPV (7.2×10^{11} PIB/ha) alone, EPV contaminated with NPV (1.8×10^{11} inclusion bodies/ha) alone, fenitrothion followed by NPV, and fenitrothion followed by EPV (+NPV). Generally, better results were obtained with the chemical/virus combinations than either chemical or virus alone. There was better foliage protection in the year of application in the plots treated with virus alone or fenitrothion/virus combinations than with fenitrothion alone and this foliage protection was also recorded the following year (Morris *et al.*, 1972, 1974). In 1979, a 40 ha plantation containing both black and white spruce trees was treated with acephate (Orthene®) at 560g AI/ha when larvae on white spruce were in the fourth instar and with NPV at 7.5×10^{11} PIB/ha 8 days later when larvae were in the fifth and sixth instars. Significant foliage protection was obtained in the year of application and in the following year (Cunningham and Howse, in press).

Although these two trials showed promising results, this is a line of research which is not being actively pursued. In attempts to initiate and maintain a virus epizootic, the aim has been to kill as many larvae as possible with virus so as to introduce a large virus inoculum pool into the environment. When used in forestry, it is felt that the addition of even low dosages of chemical insecticides reduces this virus inoculum pool and detracts from the appeal of using an environmentally acceptable biocontrol agent.

Western Spruce Budworm

When the pathogenicity of NPV and GV were compared in spruce budworm and western spruce budworm, the western species was considerably more susceptible to both viruses (Cunningham *et al.*, 1983a) and it appeared that western spruce budworm is a better candidate for regulation with viruses than the eastern species. Aerial spray trials were conducted in 1976, 1978 and 1982; 6 plots have been treated with a combined area of 424 ha (Table 3).

Table 3: Spray trials with viruses on western spruce budworm in British Columbia.

YEAR	TREATMENT	NO. OF PLOTS	TOTAL AREA (HA)
1976	NPV	1	20
1978	NPV	3	60
1982	NPV	1	172
1982	GV	1	172

In 1976, an application of 2.5×10^{11} PIB/ha on Douglas-fir trees gave disappointing results (Shepherd and Cunningham, unpublished). In 1978, three plots containing Douglas-fir trees were treated with a dosage of 7.5×10^{11} PIB/ha. Fifteen days post-spray, levels of NPV infection, determined microscopically, were 55, 87 and 25% and population reductions due to treatment were 0, 26 and 48% respectively (Hodgkinson *et al.*, 1979). In 1979 and 1980, surveys were conducted on two of the plots, the third being abandoned because of a local population collapse. In 1979, NPV infection levels were recorded as 18 and 45% and in 1980 as 7 and 17%. In 1979, population declines, compared to 1978 levels, were recorded at 51 and 62% compared to increases of 46 and 201% in corresponding check plots. Unfortunately, this trend was reversed in 1980 with populations more than doubling in the treated plots compared to substantial declines in the check plots (Shepherd *et al.*, 1982). It was felt that small plots may be unsatisfactory when long-term studies are contemplated because immigration of moths may have a profound effect on population densities.

In 1981, small Douglas-fir trees were sprayed with 3 dosages (10 fold differences) each of NPV and GV when larvae were at the peak of the third instar. The lowest dosage of GV at 1.5×10^{12} capsules/ha had a marked impact, but the lowest dosage of NPV at 2.5×10^9 PIB/ha had none, and it was considered that GV may be a better candidate as a biocontrol agent than NPV (Cunningham *et al.*, 1983b). A similar test was conducted in the US in 1981 when individual grand fir trees were treated with NPV and GV at 3 dosages (2 fold differences) at two application dates, when larvae were 50% second instar and 50% third and also when they were 10% second, 53% third and 37% fourth instar (M.J.

telzer and D.W. Scott, personal communication). They found no significant differences between the two viruses or the three dosages or any interaction between virus type and dosage. However, the GV provided better control when applied at the early timing compared to the late timing which probably reflects the longer incubation period of the GV compared to the NPV. They do not feel that either virus warrants further development since commercial preparations of *Bacillus thuringiensis* (*B.t.*) are available.

Following the results of the NPV aerial spray trials in 1978 and results of the ground spray applications in 1981 in B.C., it was decided to treat two large plots, one with NPV and one with GV to determine the long-term impact of these two viruses. This was accomplished in 1982 and two 172 a plots containing Douglas-fir trees were sprayed at budflush when larvae were at the peak of the fourth instar. The two viruses were compared on the basis of weight of lyophilized material and kg was applied to each plot in a volume of .4 L/ha using a tank mix containing 25% emulsifiable oil (Dipel 88® blank carrier vehicle) and 5% water. The actual dosage of NPV was 5.4×10^{11} IB/ha and the dosage of GV was 1.7×10^{14} apsules/ha. A high level of control was not anticipated in the year of application, but it was hoped that dead larvae remaining overwinter on the foliage would release sufficient viable virus to initiate an epizootic in 1983.

Preliminary analysis of data shows that the NPV had a greater impact than the GV on western spruce budworm in 1982 with 52% population reduction due to treatment compared to 35%. In samples of larvae reared individually in the laboratory, 66 to 80% died from NPV and 59 to 62% from GV; successful adult emergence was 53% in the check plots, ranged from 6 to 13% in the NPV-treated plot and from 12 to 24% in the GV-treated plot. Both viruses had an impact in 1983, but it was less than in the year of application. Population reduction attributed to NPV carry-over was 35% and attributed to GV carry-over was 15%. Two samples from treated and check plots were reared until death or adult emergence. Successful adult emergence was 46 and 46% from the NPV-treated plot, 50 and 42% from the GV-treated plot and 61 and 73% from the check plots (Otvos, Cunningham and Kaupp, unpublished). These results certainly cannot be regarded as dramatic, and it appears that relying on virus carry-over from one year to the next to regulate the insect population is not a viable pest management strategy.

Conclusions

Presently, lack of commercial interest in producing viruses is a major stumbling block in their development. All virus production in North America is at government establishments and the one company, Sandoz Inc., which marketed a viral insecticide, has discontinued production. If production in cell cultures becomes a viable alternative to

using insect larvae, several pharmaceutical companies, with expertise in production of viral vaccines, would probably be interested in this market. The cost of producing budworm viruses in insect larvae at the pilot plant level is extremely high. It is difficult to quote an accurate figure, but an NPV dosage of 7.5×10^{11} PIB/ha probably costs in excess of \$300/ha. This could be justified economically if virus persisted sufficiently well in the environment so as to hold the population below an economic threshold for several years or if it spread from treated to untreated areas allowing zebra stripe applications (widely spaced swaths) to be made. NPV and GV have persisted from one year to the next following some, but not all, applications. However, the incidence of infection has not been, except in rare circumstances, sufficiently high to regulate the spruce budworm population. To date, applications of viruses at budflush have virtually been applications of a very slow acting, expensive, stomach poison which sometimes gives a high level of population reduction with little or no foliage protection.

If one wants to use a non-chemical agent for spruce budworm population regulation, an obvious choice is *B.t.* which is readily available commercially at a competitive price. Numerous trials and operational applications have shown *B.t.* to be effective against spruce budworm. Considerably fewer trials with *B.t.* have been conducted on western spruce budworm, but satisfactory results have also been obtained on that species (M.J. Stelzer and D.W. Scott, personal communication).

Viruses are extremely efficient pest management tools when they act in a truly biological manner, and are probably superior to applications of *B.t.* By truly biological, one means that the virus treatment initiates an epizootic, secondary infection occurs, virus is spread from treated to untreated areas by such agents as predaceous, parasitic and scavenging insects and also, perhaps, by birds and the virus may persist from one year to the next if the insect population is not completely controlled in the year of application. The most spectacular viruses studied to date are those infecting European spruce sawfly, *Gilpinia hercyniae*, European pine sawfly, *Neodiprion sertifer*, and redheaded pine sawfly, *N. lecontei* (Cunningham and Entwistle, 1981). *B.t.* is not effective against sawflies. Douglas-fir tussock moth NPV is another outstanding virus which initiates an epizootic in the year of application. Applied on first and second instar larvae, only 10 to 30% may become infected by ingesting the spray deposit, but secondary infection causes collapse of the population (Cunningham, unpublished). Unless an excellent deposit is obtained with *B.t.*, it is not as effective as NPV for regulation of Douglas-fir tussock moth.

However, it would be most unwise to discontinue research on alternative methods of spruce budworm control and rely entirely on *B.t.* Pest managers should have a variety of options from which to choose. Presently, there are three companies in North America producing *B.t.* and problems of availability seem unlikely. There is neither evidence

of insects becoming resistant to *B.t.* nor reports of any undesirable side-effects following the use of *B.t.* Currently, viruses cannot be recommended for spruce budworm population regulation and can only be regarded as being at the experimental stage of development.

Improved methods of controlling spruce budworm with viruses are constantly being considered, although the life-cycle and behavior of spruce budworms are major insoluble problems. A continuing search is being made for more virulent virus isolates. If viruses could be kept in an infectious state on the foliage for prolonged periods, their efficacy would be greatly enhanced. Also spraying before second instar larvae emerge from hibernacula may then become a feasible strategy. A search for such tank mix adjuvants as stickers and UV protectants is being made for other viruses and other microbial pathogens and a breakthrough in this field could revitalise research on budworm viruses currently on hand. The epizootiology of spruce budworm viruses is not well studied and a better understanding of the virus - insect host - forest environment could give the answer to why applications of viruses are less than satisfactory. Perhaps the answer is spruce budworm behavior, but it may be a factor which can be modified or manipulated with relative ease.

Lastly, by far the most exciting aspect of current spruce budworm virus research is that of recombinant DNA technology. It is conceivable that the virulence, host range and resistance to UV light can be altered once the genes controlling the various viral functions are identified. Considerable progress has been made in constructing a physical map of the spruce budworm NPV genome. The next step is to produce a transcriptional map which ascribes a function to different regions of the DNA (B.M. Arif, personal communication). Genetic studies have revealed that alfalfa looper, *Auto-grapha californica*, NPV is very closely related to spruce budworm NPV and that these two viruses probably evolved from a common ancestor. A recombinant of these viruses may yield a virus which can be propagated in cabbage looper larvae, a large, easily reared Noctuid, but which still retains its infectivity to spruce budworm (B.M. Arif, personal communication). Speculation on the potential use of genetically manipulated Baculoviruses is limitless, but it will probably be several years until such viruses reach the stage of field testing. Such hurdles as public opinion, safety testing protocols and regulatory agencies will have to be overcome.

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ERYNIA RADICANS AS A MYCOINSECTICIDE FOR SPRUCE BUDWORM CONTROL

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Abstract

The entomopathogenic fungus Erynia radicans, has been under investigation for several years as a possible alternative to chemical control of the eastern spruce budworm. A commercial production method has been developed which allows the formulation of this pathogen as a mycoinsecticide. A standardized bioassay method was used to select strain RS141 as the most potent isolate. The SD_{50} was found to be 11 conidia/ mm^2 with a slope of 2.21 against 6th instar larvae and a ST_{50} at 20 C of 3.5 days. When the mycoinsecticide is applied in the field, conidia were produced for up to 5 days during wet periods. Temperature below 10 C seem to limit the fungus activity. It is recommended that the research continue with emphasis on epizootiological investigations and selection of low temperature strains.

Introduction

The entomopathogenic fungus Erynia radicans (Brefeld) Humber, Ben Ze'ev et Kenneth (syn. Entomophthora sphaerosperma Fres.) has been recognized as an important pathogen of the spruce budworm Choristoneura fumiferana Clemens, over much of its range (MacLeod 1956, 1963; Otvos et al. 1973; Vandenberg and Soper 1975, 1978). The prevalence of mycosis caused by E. radicans has been reported by these authors as ranging from a low background infection of 1% to over 90%. In Newfoundland, E. radicans also attacks the hemlock looper, Lambdina fiscellaria (Guen.) causing extensive mortality. Phenological studies (Vandenberg and Soper 1978) showed that in Maine there were four species of entomopathogenic fungi which attacked the spruce budworm. These included an imperfect fungus Hirsutella gigantea Petch, and three entomophthoralians Conidiobolus sp., Entomophaga aulicae (Reichardt in Bail) Humber and E. radicans. Of these, E. radicans

was the first to cause mortality each spring being most prevalent during the 5th larval stage. The other two Entomophthoraliens did not generally occur until the 6th instar or pupae. H. gigantea was never abundant making it impossible to draw any conclusions concerning its phenology. However, spruce budworm larvae killed by H. gigantea from the previous season, were occasionally found in the spring on spruce and fir branches. When these specimens were placed in petri dishes at high RH, the fungus would sporulate. Since it would be important to initiate disease early in the spruce budworm population cycle to prevent defoliation, E. radicans was chosen for further study as a potential biological control agent.

The Pathogen

The spruce budworm pathogen, E. radicans, undergoes a typical entomophthoran life cycle. It survives during the winter in the resting spore state. These spores are multinucleate when newly formed. As they mature, the spore wall thickens and the number of nuclei are gradually reduced until the spore becomes bi-nucleate. At this stage the spore has entered dormancy and can not be readily germinated. McCabe et al. 1984 (in press) describe this process and give presumptive evidence that these nuclei fuse a few hours prior to the breakdown of the spore wall during the germination process. If this is in fact the fusion nucleus, then it represents the sexual stage of the fungus. Perry and Latge (1982) reported obtaining very high germination of Conidiobolus obscurus after storage at 4 C for several months. Perry et al. (1982) obtained similar results with E. radicans (reported as Zoopthora radicans) resting spores.

Under field conditions, the resting spores are likely found in the forest litter or on the tree bark. Evidence from other closely related fungi, Erynia canadensis (MacLeod, Tyrrell et Soper) from the woolly pine needle aphid, Schizolachnus piniradiatae (Davidson), would indicate that the resting spores may not survive exposure to very low winter temperature (Wallace et al. 1976). On return to favorable conditions for germination, the resting spores produce numerous germ conidia which are actively discharged and become air borne. Infection takes place when these spores come into contact with a susceptible host. It has been demonstrated in the laboratory that the

fungus produces predominantly conidia when infecting 2nd, 3rd, and 4th instar spruce budworm larvae and resting spores from infected 5th, 6th instar larvae, pupae, and adults. The primary conidia are responsible for the current season transmission of the mycosis. These spores are also air borne and cause infection on contact. They have the ability to produce secondary spores of two types. If the spore fails to reach its host, it usually produces a capillospore which is almond shaped and forms at the end of a very thin tube. The capillospore is produced at right angle to the substrate on which the conidia has landed. This positions the secondary spore for better contact with any larva which might walk over the surface of the plant. The second spore type is morphologically similar to the primary conidia except it is smaller. It is also discharged and can become air borne. Conidial formation requires the fungus to either be in contact with free water or at 100% RH.

Development

The basic concept for use of E. radicans as a biological control agent for the spruce budworm was application as a mycoinsecticide. This requires the solution of several well defined critical problems. First it is necessary to select a strain of the fungus with high pathogenicity and virulence. Once an appropriate strain has been identified, the second step is to develop a commercially acceptable method of production. The least expensive production method for microorganisms is the use of deep tank fermentation technology. Fortunately E. radicans was known to be easily grown on liquid media. The final step in this process is the selection of an appropriate formulation.

Strain Selection: Central to the development of any microbial agent for insect control is the ability to determine pathogenicity and virulence. Initially it is necessary to choose a suitable strain for development and then monitor its quality during production. Traditionally, dose-mortality responses have been analyzed for SD_{50} and ST_{50} as a measure of strain effectiveness. Since "between-experiment" variability is generally high, a standard strain is selected to be included in all bioassays. The potency of the test material is then compared relative to the standard. In general, it is necessary to keep all sources of variation to a minimum so dose-mortality will reflect only pathogen response. The two major sources of variability are the host and the pathogen. It was determined in early experimentation that budworm

larvae infected with chronic levels of microsporidia would result in erratic E. radicans bioassays. When these larvae were stressed by infection from the fungus, they succumbed quickly. In most instances, diagnosis would reveal large numbers of protozoan spores and very few hyphal elements. A protozoan free colony was established and used to bioassay the fungal strains. The test insects were further standardized by using only 6th instar larvae which had moulted within the previous 24 hrs. Initial bioassays with E. radicans depended upon producing conidial showers from mycelial mats (Vandenberg and Soper, 1979). Although it was possible to obtain SD_{50} values, doses were highly unpredictable. It was found that spores were distributed unevenly over the infection court and the rate of sporulation could change rapidly over a brief interval (Table 1).

Table 1: Conidia of E. radicans Produced From Mycelia Mats at 15 min. Intervals

Rep	Time			
	15	30	45	60
1**	3(0.5)	4(0.7)	2(1.6)	2(0.9)
2*	10(2.3)	30(20.3)	37(25.1)	36(26.0)
3	13(10.1)	13(4.8)	18(9.5)	25(12.1)
4**	3(1.8)	6(4.0)	11(8.6)	28(16.1)

Mean with Standard Deviation

* Significant at 5%

** Significant at 1%

Clearly from these typical data, significant changes in sporulation rates can occur within a 15 minute exposure while the high standard deviations are indicative of an uneven distribution. To overcome this problem, experiments were conducted to develop techniques which would allow exposure of budworm to precise and controlled quantities of conidia. The first problem was to produce a stable, viable and uniform suspension of conidia. Ten wetting agents were screened for ability to wet the spores without effecting their ability to germinate and infect insects (Table 2).

Table 2: Effect of Wetting Agents on Conidia of E. radicans Conidia

Agent	Ability to Wet	Effect
Agrimul SS	Fair	Toxic
Agrimul 26	Poor	None
Atplus 401	Good	Toxic
GAFAC RE610	None	Toxic
Sellogen W	Poor	Toxic
Sponto 500T	Fair	Toxic
Triton X100	Excellent	Toxic
Tween 80	Fair	None
Tween 20	Fair	None

The best combination proved to be an aqueous solution containing a suspending agent, 0.1% Atmos 300, and 0.25% Tween 80. Storage tests showed high viability was retained for at least 48 hrs at either 4C or 20 C. Beyond that period, secondary germination within the suspension made determination of primary conidial survival difficult. In one test, however, it appeared that over 40% survived at 4 C for 9 days. For the purposes of the bioassay dose preparation, it was only necessary for the conidia to survive a few hours between collection and utilization. The standardized technique was as follows:

1. Mycelial mats formed as described above under production, are inverted over a petri dish (100 mm) containing approximately 5 ml of the Atmos 300 / Tween 80 solution. The conidia which are showered into the solution are collected every 2 hours by pipetting off the suspension and are then stored at 4° C to prevent germination.

2. The conidia are pooled from all dishes and centrifuged at 1000 rpm in a swinging bucket rotor for 10 minutes.

3. The spore pellet is resuspended in Atmos 300/Tween 80 to the desired volume using a vortex mixer.

4. The spore suspension is forced through a 200 mesh screen 10 times to reduce spore clumps.

5. Spore counts are made with a haemocytometer to determine final dilution. With current spray techniques, 0.5 ml of 1×10^6 to 4×10^6 conidia/ml yields a dose of approximately 100 spores/mm².

6. The spray apparatus consists of a modified JJ nozzle (Spray Systems Inc.) in which the normal spray input opening is plugged and replaced by a

chromatography injection port. The top of the spray nozzle is drilled and tapped to accept the port. Air pressure is controlled, using a standard regulator and a flow valve, to 700 gm/cm².

7. A plexiglass box with a 100 mm diameter opening directly in the target area of the spray is placed at approximately 15 m from the spray nozzle. The opening is covered with a screen and a vacuum is placed on the box using an ordinary vacuum cleaner connected by means of a tube on the side. This serves to immobilize the test insects and results in a more uniform spray pattern.

8. Test insects consist of 40 6th instar budworm larvae per dose which are placed under the spray nozzle together with a cover slip.

9. Although approximate dosage is determined by varying the number of conidia in suspension, the actual dosage sprayed on the insects is determined by counting 10 random fields on the cover slip and expressed as spores/mm².

10. Five dosages are selected to bracket the SD₅₀ and the experiment is repeated 4 times.

11. The insects are placed at high relative humidity without food for 24 hours following exposure to the conidia; at which time they are returned to normal rearing conditions. All larvae are reared individually at 20 C with a 16 hour photophase. They are checked daily for mortality and the dead insects are examined microscopically for disease. The assay is terminated in 6 days.

The standard E. radicans isolate is RS141. This strain has a common SD₅₀ of 11.0 conidia/mm² and a slope of 2.21 against 6th instar spruce budworm larvae (Table 3). The ST₅₀ for the standard is 3.5 days at 20° C with a range of 2 to 4 days. Comparison with RS491, for example, showed the standard to be 4.5 times more potent. In fact RS141 proved to be the most active strain tested and was thus selected for development as an mycoinsecticide.

Table 3: Response of Spruce Budworm Larvae (L₆) to Conidia of E. radicans

Assay	SD ₅₀	95% C.I.	Stand. Error
1	9.3	5.2-15.1	0.45

2	10.2	6.0-16.4	0.59
3	11.1	6.5-18.0	0.54
4	13.4	6.2-21.1	0.52

Common SD₉₀ = 11.0 S.E. = 1.76
Common Slope = 2.21 S.E. = 0.26
Heterogeneity = 1.21 G(0.95) = 0.07

Production: Strains of *E. radicans* were kept in 8 % glycerol in ampules frozen under liquid nitrogen. This served as a source of material for production experiments. The ampules were removed from storage and the fungus rapidly thawed in 35 C water. The fungus mycelium was then transferred to mycological agar containing 1% yeast extract. When the fungus was actively growing, it was transferred to 500 ml shake flasks containing 75 ml of sterile liquid medium. Several liquid media are suitable but one which was frequently used was: corn syrup 40 ml; yeast extract 10 gm; peptone 10 gm; water 950 ml. The medium was adjusted to pH 6.8. The fungus was incubated at room temperature (25 C) on a rotary shaker at 300 rpm. When the fungus entered log growth phase, usually in 96 hrs, it was used to inoculate fresh media. A 10% inoculum level was used, viz. 7.5 ml of suspended mycelium was added to 75 ml of fresh medium. When the fungus reached log growth phase again, usually in 48 hrs, it was used to inoculate 25 l fermentation vessels. The inoculation rate was also 10%. The vessels were autoclavable plastic carboys which had been modified to permit compressed air to be bubbled through the medium from the bottom by means of a plastic tube. The fermentation process was allowed to progress to the end of log growth phase, usually 36 hrs, and then the mycelium was harvested. The harvesting process consisted of filtering the mycelium onto cheese cloth in a specially constructed box which allowed the liquid to be removed by vacuum. The fungus was washed several times with deionized water to remove residual media. The mats were then placed on wire racks and allowed to incubate for an additional 2-3 hours. At this stage the fungus was dried according to a process now being considered as a public patent (McCabe and Soper 1982 patent pending).

Growth Chamber Studies

Methods: Preliminary experiments with *E. radicans* against spruce budworm were conducted on potted balsam fir (55 cm) under controlled environmental conditions. The trees were kept at 4 C until required for tests. Several weeks prior to the experiments, the

trees were removed from cold storage and placed in the greenhouse to promote bud growth. Each test consisted of 50 4th or 5th instar laboratory reared larvae. These were placed on the potted trees and allowed to establish. The trees with the insects were placed in a spray chamber and treated with a standard dose of the mycoinsectide. The dosage was either 1 gm (10 to 7th conidia) or 10 gm (10 to 8th conidia). The fungus was applied with a 8002 T-jet fan spray nozzle placed approximately 40 cm from the top of the tree. The tree was rotated about 2.5 revolutions on a turntable during the spray period. A sample of the fungus was assayed for ability to produce conidia. Following treatment, the balsam fir trees were placed in environmental chambers set at various temperatures according to the experimental protocol. Relative humidity was that of the ambient conditions in the growth chambers or was raised to ca. 100% by placing plastic bags over the trees. Following 24 hrs of exposure to the test conditions, the insects were removed from the trees and placed individually in cups on artificial diet. They were checked daily for disease. The experiments were terminated 5 days post application and all insects examined for the presence of infection.

Results: An experiment was conducted to determine how soon after spraying the insects became infected. In this experiment, 10 trees were sprayed with 1 gm of fungus powder in 50 ml of water. Following application, 50 4th or 5th instar larvae were placed on each tree. They were then placed at 100% RH at 20 C in a 16 hr photoperiod. The budworm were removed from each of 2 trees at 0, 5, 24, 30, and 48 hrs and reared individually. The infection observed at 0 and 5 hrs (2%-3%) probably came from spores which were carried into the rearing dishes on the exposed budworm. Most of the infection occurred between 5 and 24 hrs (28%) although an increase was observed at 48 hrs (41.5%) when the experiment was terminated.

Low overnight temperatures of 4 and 10 C for 8 hrs were also investigated for their influence on infection levels in the growth chambers. These were compared to a constant temperature of 16 C in a 16 hr photoperiod. In addition, the tests were designed to compare high (100%) and moderate (85%) RH during the day and 3rd instar vs 5th instar. The results show that moderate RH during the day did not influence the infection rate. However, 5th instar larvae were more vulnerable to

infection than 3rd instar larvae under these test conditions. Overnight temperatures between 10 and 16 C resulted in similar infection levels (36.0%--46.5%) while tests conducted at 4 C produced reduced infection rates (3.0%--16.5%). The general conclusions drawn from these and similar data were:

1. E. radicans is capable of causing significant spruce budworm mortality when applied as a mycoinsecticide.
2. Significant infection occurs within 24 hrs of application under conditions of high relative humidity.
3. Infection can take place under early spring conditions in Maine despite low night-time temperatures (4 C). However, infection rates are much higher at more elevated minimum daily temperatures (13 C).

Field Performance

Field Methods: Observations were made under field conditions to determine the influence of microclimatic conditions on the revival of the powdered mycelium of E. radicans and its ability to produce conidia. The study site was located in Township 34, Maine at the intersection of St. Regis stud mill road and logging road 30 00 00. The area consisted of an even age stand of balsam fir with trees about 3 to 6 meters high. The microclimate was monitored using data logging devices (Datapod, Omnidata, Logan, Utah) which automatically recorded information on EPROM computer chips. These were changed at weekly intervals and read directly into a Prime computer (USDA, ARS Beltsville, MD) by means of a computer terminal located at the field station. The information included leaf temperature, leaf wetness, rainfall, solar radiation, wind speed and wind direction. This data was summarized daily using SAS analysis procedures. A spore trap (Burkhard) which recorded the number of conidia collected per cubic meter of air per hour, was run continuously throughout the test period. The spore tapes were removed daily and the number of spores collected per hour were recorded by scanning under a compound microscope at 200x magnification.

The mycoinsecticide (100 gm) was suspended in one gallon of water with the aid of 8 g of a special adjuvant (Table 4).

Table 4: Adjuvant Developed for the E. radicans Mycoinsecticide

Ingredients	% by wt.	Supplier
Kelzan S	14.4	Kelco Co.
SGP 104	30.0	Henkel
PUP K-60	33.3	GAF Corp.
CMC	22.3	Hercules

The suspension was sprayed with a backpack mist blower (Solo Inc.). This was calculated to produce 10 to 9th conidia per tree. Application was made to each of 3 trees and replicated 4 times in a randomized block. Treatments were 1 = 4th instar, 2 = 5th instar, 3 = 6th instar and C = untreated check. Weekly samples of two 46 cm branches were collected from each sample tree. The budworm larvae were counted, removed and held for 6 days on artificial diet to check for infection. In addition, a sample of field collected budworm were exposed to conidia from the rehydrated fungus powder held at 100% RH for 24 hrs and then reared for 6 days to check the infectivity of the material.

Laboratory Methods: Powdered mycelia from the same production was used in both the field investigations and laboratory studies. The influence of temperature on revival of the mycelia and subsequent spore production was determined at 5, 10, 15 and 20 C. This was tested by placing 10 mg of powder on no. 3 Whatman filter paper in a 35 cm petri dish containing 2% water agar. The dish was inverted over an aqueous solution of 0.2% maleic acid plus 1.0% Triton-X 100 and sealed with parafilm. The water agar provided sufficient moisture to insure revival and sporulation, while the solution prevented germination. Spores were collected at 2 hr intervals, beginning at 4 hrs of incubation through 18 hrs, then continued at 26, 30 and 96 hrs. The spores were suspended in 10 ml of malic acid solution. A haemocytometer was used to count the number of spores in suspension. The treatment was replicated 4 times and the experiment was repeated 3 times. Mycelial mats were produced using the same method as in the patent process, but the fungus was allowed to sporulate rather than be immediately dried. These spores were used to test the influence of temperature on germination. Water agar (2%) in 35 cm petri dishes was exposed to the spore showers from the mats. The spores were covered with a glass coverslip to prevent respiration, and then incubated at 5, 10,

15, and 20 C in both light and dark. Germination was determined under a dissecting microscope at 50x magnification by counting the number of germ tubes from a random sample of 100 spores. The treatments were replicated three times and the experiment repeated three times.

Results: The fungus was applied on June 3 (14.30 hrs), June 16 (12.00 hrs), and June 19 (18.00 hrs). There were intermittent rain showers during the first application. Nevertheless, the fungus powder did dry sufficiently to adhere to the balsam fir needles, but never dried to the point of hardness. The needles remained wet throughout the following 52 hours. Sporulation began at 23.5 hrs after application, with heavy conidial production between 23.00 hrs June 4 to 03.00 hrs on June 5. Sporulation stopped at 09.00 hrs and resumed again at 15.00 hrs, continuing uninterrupted until noon on June 6. Sporulation began again at 15.00 hrs and continued with varying degrees of intensity until the morning of June 9. The second application was during bright, sunny weather. The fungus particles dried rapidly to a very hard consistency. Sporulation did not occur until 20.00 hrs on June 18, 2 days following application. Samples of needles with fungal particles were removed from the sprayed trees and incubated at room temperature and 100% RH. All particles revived and produced spores. The delay in sporulation was caused by a thick coating formed by the protective adjuvant. It apparently took several days for the fungus to rehydrate and grow through the coating. Nevertheless, the fungus stayed alive during a very warm, dry period. The third and final application (June 19) was made during a warm evening with dew formation occurring within 2 hrs after spraying. Sporulation began very quickly and was most abundant from 01.00 to 06.00, stopping altogether at 09.00 hrs the next day. Sporulation was light the following evening in spite of the lack of leaf wetness. The experiment was terminated June 21.

The Spray applications were timed to correspond with peak 4th, 5th, and 6th instars. These targets were met, however, it is also evident that the population in the test site was fairly low beginning at 4.5 total larvae/46 cm branch and falling to about 1 at the end of the experiment. None of the budworm collected and reared showed any sign of infection. However, a significant percentage of the budworm exposed to conidia from the fungus powder in the field laboratory became in-

fected. This indicated that either population density was too low, inoculum levels were too low, or some other environmental factor was limiting. Although all of these are possible, laboratory experiments indicated that low temperature may have been the problem. This is corroborated by the earlier growth chamber studies. It was evident that conidial production for rehydrated fungus powder was greatly influenced by temperature. Sporulation began in 4 hours at 20 C, 6 hrs at 15 C, 10 hrs at 10 C, and 16 hrs at 5 C, with total number of spores falling off drastically below 15 C. At 18 hrs for example, the previous 2 hrs had produced the following conidia (x 10 to 4th): 5 C = trace; 10 C = 3; 15 C = 12; and, 20 C = 21. Germination is also limited by temperature with the added complication that in the absence of light, spore production was further reduced.

Discussion

It is apparent that there is some factor in the environment which prevented E. radicans from infecting the budworm under field conditions. It was shown that the isolate selected for production (RS141) was capable of infecting 6th instar larvae at relatively low doses (11 spores/mm²), and would kill them quickly (2-4 days) in the laboratory at 20 C. Further, the material formulated as a mycoinsecticide was shown to retain pathogenicity. There are several possible explanations. As discussed above, low temperature (10 C or below) increases the time required for the fungus to produce spores and then for the spores to germinate and cause infection. At 10 C the total time elapse would be about 24 hrs viz. 14 hrs for production plus 10 hrs for germination and penetration. This is unrealistic under field conditions. First of all, the fungus requires free water to rehydrate. This is usually present in the form of dew which forms overnight giving an activity period of 8 to 12 hrs although this time can be extended during rainy weather. Nevertheless, it is fairly common for the night temperature to fall below 10 C or at least be well below 20 C. Even though the field data showed sporulation occurred, there may not have been time enough for germination of the spores and penetration of the resulting infection tube before return to low RH. The second problem might have been the relatively low host population density, i.e. 2 to 4 larvae/46 cm branch. Finally, it was assumed that 10 to 9th

conidia per tree was a "high" dose. This may in fact have been relatively low, especially since the fungus particles were difficult to find and presumably lost 48 hrs after application.

Future Directions of Research

This pathogen, Erynia radicans, has been shown to cause extensive mortality in eastern spruce budworm populations without the intervention of man. The question is can this fungus be manipulated in some way to effect population control of the spruce budworm at other times. The answer is likely yes however in spite of the extensive research effort that has been conducted to date the research must be continued if we are to answer this question. The major problem of production has been solved and methods for bioassay developed. What remains now is to select an isolate that is suited to low temperature development and to conduct extensive epizootiological studies to determine the important factors which limits disease spread and intensity. There are researchable approaches to the problem of low temperature. Small quantities of the mycoinsecticide was produced from several E. radicans spruce budworm isolates chosen at random from the USDA, ARS culture collection. This material was incubated at 10 C as previously described and the number of spores produced determined at 6, 7, and 8 hrs (Table 6).

Table 6: Conidial Production from Various E. radicans Mycoinsecticides at 10 C

Strain	6	7	8
RS50	0	0	0
RS88	0	0	0
RS141	0	0	0
RS143	0.25	1.00	2.85
RS145	0	0	0
RS162	0	0	0.05
RS185	0.05	0.10	0.15

Conidia/100 mg x 10 to 4th

It is heartening to see that at least 2 isolates (RS143 and RS185) showed activity at 6 hrs, while RS141 used in field trials did not sporulate even at 8 hrs. Selection for low temperature activity can be conducted under laboratory conditions through a series of re-isolations and production experiments. Field investigations should

continue with the objective of determining the "window of vulnerability" in the spruce budworm cycle to attack by E. radicans. Epizootiological studies should be initiated to develop a systems model for the Erynia radicans /spruce budworm interaction. This model could be used in simulation studies to develop an optimum strategy for using a mycoinsecticide against the spruce budworm.

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THE EFFECT OF ERYNIA RADICANS ON FOOD CONSUMPTION,
UTILIZATION AND FECUNDITY BY THE SPRUCE BUDWORM,
CHORISTONEURA FUMIFERANA.

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Abstract

In food consumption and utilization studies, observations were confined to a period of 5 days after which mortality of Erynia radicans larvae began to occur. Mortality due to the fungus was 76 and 83% in male and female larvae, respectively. In control larvae the pupation rate was over 95%. Control larvae of both sexes consumed significantly ($P = 0.05$) more food than fungus treated larvae on day 4 and 5. Treated as well as control larvae showed a continuous gain in body weight up to day 3, following which treated larvae of both sexes gained significantly ($P = 0.05$) less weight than the control. Fungus infected larvae were also less efficient in converting ingested and digested food to body substances (ECI and ECD) on day 4 and 5 in females and on day 5 in males. Pupae of both sexes from treated larvae weighed less than the control. Fecundity of adults arising from fungus treated larvae was reduced by approximately 36.4% compared with the control.

Introduction

Erynia radicans (= Zoopththora radicans = Entomophthora sphaerosperma) is among the more promising of microbial agents for the control of the spruce budworm, Choristoneura fumiferana and has a potential for commercial development as a microbial insecticide (Weatherston and Retnakaran 1975; Vandenberg and Soper 1979). However, an important drawback of mycopathogens in the control of insect pests is the time taken to kill the host. Generally, mortality of infected larvae occurs in 4-8 days after treatment (Mohamed et al. 1982) during which larvae continue to feed, presumably causing damage. Therefore, it would be beneficial if it could be ascertained that fungal infection of the host can reduce food consumption. This would aid in assessing the suitability of the pathogen for use in insect pest management, particularly in a forest situation where the foliage can tolerate moderate feeding damage.

Most reported studies dealing with the control of insects with pathogens have dealt mainly with the direct effect on the host and have been evaluated in terms of percent mortality. Little attention has been focused toward the evaluation of the effect of infection on food consumption and the general reduction of the biological

potency of the host (Jasic 1961). Ramakrishnan and Chaudhari (1974) studied the effect of a nuclear polyhedrosis virus (NPV) on the consumption and utilization of food by the Egyptian cotton leaf worm, Spodoptera litura. They found that food consumption and weight gain of virus infected larvae were significantly lower than the control. Drake and McEwen (1959) reported that the cabbage looper, Trichoplusia ni showed decreased food consumption following infection with NPV. Thomson (1958) showed that the microsporidian, Perezia fumiferanae retarded larval and pupal development, reduced fecundity and adult longevity of C. fumiferana. Larvae of Heliothis zea infected with Nomuraea rileyi showed significantly less food consumption and utilization than the control group (Mohamed et al. 1982).

The purpose of this study was to determine the effect of E. radicans on food consumption, utilization and fecundity of C. fumiferana.

Materials and Methods

Larvae and Fungal Cultures. - Overwintering second instar spruce budworm larvae were obtained from the Insect Pathology Institute, Saulte Ste. Marie, Ontario, Canada. Larvae were reared on Bio-Serv Spruce Budworm diet #9769, dispensed in about 15-20 ml aliquots into 30 ml plastic cups. Four to six larvae were placed in each cup and reared at 22.5°C with a photoperiod of 16 hr light and 8 hr darkness.

The culture of Erynia radicans was obtained from the laboratory of Dr. R. S. Soper, U.S.D.A. ARS, Insect Pathology Unit, Boyce Thompson Institute, Ithaca, N.Y. The initial sample of this fungus was isolated from a field collected spruce budworm larvae (Vandenberg and Soper 1979). It was grown on 70% modified egg-yolk medium (EY) in darkness at 25°C according to Soper et al. (1975.) Sporulation was induced according to the method of Vandenberg and Soper (1979). Several 250 ml flasks each containing 75 ml of CYP liquid medium (4% corn syrup, 1% yeast extract, 1% phytone-peptone in distilled water) were inoculated with mycelia grown on EY, and continuously agitated in a controlled environmental shaker (New Brunswick Scientific Co. Inc.) at 25°C. When the culture reached the exponential growth phase (4-5 days), 5 ml of each culture was transferred to fresh CYP and allowed to grow for 2-3 more days. Then the medium was filtered and the remaining mycelia rinsed several times with sterile distilled water. After the excess moisture was drained off with paper filters, mycelia were placed in plastic Petri dishes (90 x 15 mm) and exposed to continuous fluorescent light for 24 hr at 20°C to stimulate sporulation.

Treatments

1. Food consumption and utilization. - Fifth instar larvae were used in all tests. The age of the larvae was determined according to the method of Retnakaran (1973). Larvae were

sexed as described by Koller and Leonard (1981). One hundred 5th instar larvae of each sex were placed in plastic cups individually and starved for 8 hr to empty their gut contents of residual food. Eighty larvae from each sex group comprised the untreated control group. A similar number of larvae were treated with E. radicans spores as described by Vandenberg and Soper (1979). The dose was estimated by exposing Petri dishes (100 x 15 mm) containing 2.5% sterile distilled water agar to sporulating cultures identical to those used in larval treatments. Spore concentration was estimated (spore/mm²) by counting a random field in each of 10 areas in the dish (Vandenberg and Soper 1979). In preliminary tests, several groups of larvae were exposed to sporulating cultures at varying times (15 to 90 min.) An exposure time of 45 min. giving 39 ± 5.7 spores/mm² was the most appropriate in terms of mortality and survival of the larvae.

After treatment, larvae were held in individual Petri dishes (100 x 15 mm) lined with filter paper moistened daily with sterile distilled water. Each treatment was replicated 4 times with 10 larvae. Test larvae were held in an environmental growth chamber at 22.5°C with a photoperiod of 16 hr light and 8 hr darkness.

Larvae were individually provided with pre-weighed 5 mm diet plugs which were replaced daily. Food consumption and weight gain were determined by recording the initial weight of the larvae and diet, followed by recordings of the larval weight, feces and diet consumed every 24 hr. Data from these observations were used to determine food consumption and utilization. Diet consumed was corrected for moisture evaporation as described by Brewer and King (1979). The indices (Waldbauer 1968) to determine the efficiency of utilization were as follows:
a) Approximate digestibility which is the percentage of food ingested that is retained or utilized by the larvae:

$$(AD = \frac{\text{wt of food ingested} - \text{wt of feces}}{\text{wt of food ingested}} \times 100)$$

b) Efficiency of conversion of ingested food to body substances which is an overall ability of the insect to utilize ingested food for growth:

$$(ECI = \frac{\text{wt gain}}{\text{wt of food ingested}} \times 100)$$

c) Efficiency of conversion of digested food to body substances decreases as the digested food metabolized for energy increases:

$$(ECD = \frac{\text{wt gained}}{\text{wt of food ingested} - \text{wt of feces}} \times 100)$$

The data were analyzed by the analysis of variance and the Duncan's New Multiple Range Test (1955).

2. Fecundity. - One hundred 5th instar larvae of each sex were treated with E. radicans and placed in plastic cups containing diet. A similar number comprised the untreated control. Larvae were reared as described earlier and observed daily for mortality and pupation. Pupae were weighed

within 24 hr of pupation and placed in the original cups. Adults used for oviposition were reared in individual containers (Stehr 1954). Branches of balsam fir, Abies balsamea¹ were used for oviposition. Each test was conducted over a period of 4-6 days, with daily removal and counting of egg masses. The number of eggs was determined by measuring the length and width of each egg mass as described by Bean (1961).

Results and Discussion

1) Food consumption and utilization. - Mortality of E. radicans treated larvae started on day 4 post treatment. Thus observations for food consumption and utilization were done for 5 days. On day 6 most of the treated larvae were dead. Mortality in fungus treated larvae was 76% in males and 83% in females. In the control 95% of males and 97.5% of the females pupated.

Table 1 shows the amount of food consumed by treated and control larvae. The amount of food consumed by treated larvae was significantly ($P = 0.05$) lower on day 4 and 5 post treatment for both sexes. Male and female control larvae showed a constant increase in food intake throughout the observation period. The average daily intake for the treated and control female larvae was 50.2 and 77.06 mg and for the males it was 60.4 and 75.9 mg respectively.

Table 1: - The effect of Erynia radicans on food consumption (mg) of Choristoneura fumiferana larvae.^{a/}

DP ^b	Control	Fungus treated
Female		
1	67.3 ± 19.0a	59.4 ± 27.0a
2	66.2 ± 4.0a	60.9 ± 3.0a
3	60.7 ± 7.0a	51.5 ± 8.0a
4	94.2 ± 18.0a	40.2 ± 7.0b
5	96.9 ± 16.0a	39.0 ± 10.0b
Male		
1	56.3 ± 12.0a	61.8 ± 10.0a
2	71.4 ± 12.0a	78.4 ± 10.0a
3	67.4 ± 2.0a	57.3 ± 10.0a
4	90.6 ± 7.0a	54.9 ± 9.0b
5	93.9 ± 5.0a	49.3 ± 6.0b

^{a/} Means followed by a common letter horizontally do not differ significantly from each other ($P = 0.05$).

^{b/} Days post treatment.

The weight gain of treated and control larvae is presented in Table 2. Fungus treated larvae of both sexes showed significantly ($P = 0.05$) less weight gain on day 4 and 5. The average daily weight gain for the treated and control

^{1/} Specially ordered for us by a local garden and nursery center.

female larvae was 4.38 and 8.64 mg respectively. Similarly for the males the average weight-gain was 3.98 mg for the treated and 7.38 mg for the control group. The amount of feces produced in the treated larvae was significantly lower for both sexes on days 3, 4 and 5 (Table 3).

Table 2. - The effect of *Erynia radicans* on weight gain (mg) of *Choristoneura fumiferana* larvae.^{a/}

DP ^{b/}	Control	Fungus treated
Female		
1	5.8 ± 3.0a	4.9 ± 0.2a
2	6.4 ± 1.0a	7.5 ± 2.0a
3	6.3 ± 5.0a	4.8 ± 1.0a
4	10.9 ± 3.0a	2.3 ± 1.0b
5	13.8 ± 2.0a	2.4 ± 1.0b
Male		
1	3.7 ± 0.9a	3.0 ± 1.0a
2	7.4 ± 2.0a	6.1 ± 1.0a
3	8.5 ± 0.3a	5.2 ± 1.0a
4	7.6 ± 1.0a	2.9 ± 1.0b
5	9.7 ± 4.0a	2.7 ± 1.0b

a/ Means followed by a common letter horizontally do not differ significantly from each other (P = 0.05).

b/ Days post treatment.

Weight gain and fecal production are directly related to the amount of food consumed (Ramakrishnan and Chaudhari 1975). The decrease in the values of these parameters in treated

Table 3. - The effect of *Erynia radicans* on feces production (mg) by larvae of *Choristoneura fumiferana*.^{a/}

DP ^{b/}	Control	Fungus treated
Female		
1	4.1 ± 1.8a	4.7 ± 1.0a
2	7.3 ± 1.4a	6.9 ± 2.6a
3	12.0 ± 1.5a	4.6 ± 1.0b
4	15.0 ± 2.0a	2.7 ± 1.0b
5	17.6 ± 2.0a	2.2 ± 1.0b
Male		
1	4.5 ± 1.0a	4.0 ± 1.4a
2	4.3 ± 2.0a	4.4 ± 3.0a
3	7.5 ± 2.9a	4.3 ± 2.0b
4	13.2 ± 2.0a	3.6 ± 1.0b
5	20.0 ± 5.0a	3.7 ± 2.0b

a/ Means followed by a common letter horizontally do not differ significantly (P = 0.05).

b/ Days post treatment.

larvae can be attributed to reductions in food consumption of the larvae (Table 1). Reduction in food consumption, weight gain and fecal production in infected larvae have been previously reported by Mohamed et al. (1982) for *H. zea* infected with *N. rileyi* and by Ramakrishnan and Chaudhari (1975) in *S. litura* infected with NPV.

A more direct relationship between these parameters can be observed if we consider the total food consumption, total weight gain and total fecal production (Table 4). The total food consumption in male and female was significantly lower (P = 0.05) than that of the control. This

Table 4. - Total food consumption, weight gain and fecal production (mg) by larvae of *Choristoneura fumiferana* infected with *Erynia radicans*.^{a/}

Parameter ^{b/}	Female		Male	
	Con	FT	Con	FT
FC	385.3a	251.0b	379.5a	302.0b
WG	43.2a	21.9b	36.9a	20.1b
FP	56.5a	21.1b	59.5a	20.0b

a/ Means followed by a common letter horizontally for male and female separately do not differ significantly (P = 0.05).

b/ Con = Control, FT = Fungus treated, FC = Food consumption, WG = Weight gain, FP = Feces production.

reduction in food consumption was approximately 20 and 35% for the treated male and female larvae respectively. Similarly, the total weight gain and fecal production were significantly lower (P = 0.05) in the treated larvae of both sexes indicating that these indices were directly related to the amount of food consumed.

2) Food utilization. - The approximate digestibility (AD) values are summarized in Table 5.

Table 5. - Approximate digestibility (AD) of the larvae of *Choristoneura fumiferana* infected with *Erynia radicans*.^{a/}

DP ^{b/}	Control	Fungus treated
Female		
1	93.9 ± 11.4a	92.2 ± 7.6a
2	89.0 ± 10.8a	88.7 ± 12.7a
3	80.2 ± 11.8a	91.1 ± 16.7a
4	83.5 ± 8.3a	93.3 ± 11.2a
5	81.8 ± 12.8a	94.5 ± 13.6a
Male		
1	92.0 ± 8.4a	93.5 ± 11.2a
2	94.0 ± 8.7a	94.4 ± 14.9a
3	88.9 ± 11.1a	92.2 ± 13.7a
4	85.4 ± 12.6a	93.4 ± 9.8a
5	78.7 ± 6.9a	92.5 ± 6.2b

a/ Means followed by a common letter horizontally do not differ (P = 0.05).

b/ Days post treatment.

No significant difference (P = 0.05) was observed between the control and the treated group in the female larvae. In males the AD for the control was significantly lower on day 5. The gross efficiency (ECI) and the net efficiency

(ECD) showed an identical trend (Table 6, 7). In the female treated larvae, both ECI and ECD values were significantly lower ($P = 0.05$) than the control group on day 4 and 5, while in the males the ECI and ECD of treated larvae were significantly lower on day 5 only.

Table 6. - Gross efficiency (ECI) of the larvae of *Choristoneura fumiferana* infected with *Erynia radicans*.^{a/}

DP ^{b/}	Control	Fungus treated
Female		
1	8.6 ± 3.7a	8.2 ± 2.2a
2	9.7 ± 9.3a	12.3 ± 5.0a
3	10.4 ± 6.3a	9.3 ± 6.4a
4	11.6 ± 3.4a	5.7 ± 3.5b
5	14.2 ± 8.6a	6.0 ± 4.2b
Male		
1	6.6 ± 2.3a	6.3 ± 3.0a
2	10.4 ± 4.2a	7.8 ± 5.6a
3	12.6 ± 3.4a	9.0 ± 4.1a
4	8.4 ± 2.0a	5.3 ± 3.5a
5	10.3 ± 3.3a	5.5 ± 3.9b

^{a/} Means followed by a common letter horizontally do not differ ($P = 0.05$).

^{b/} Days post treatment.

Table 7. - Net efficiency (ECD) of the larvae of *Choristoneura fumiferana* infected with *Erynia radicans*.^{a/}

DP ^{b/}	Control	Fungus treated
Female		
1	9.2 ± 3.8a	8.6 ± 2.2a
2	10.9 ± 5.8a	13.9 ± 6.1a
3	10.7 ± 5.8a	10.2 ± 4.4a
4	13.9 ± 4.1a	6.2 ± 1.6b
5	17.4 ± 8.9a	6.4 ± 3.9b
Male		
1	7.1 ± 2.3a	6.8 ± 1.0a
2	11.0 ± 4.6a	8.2 ± 3.3a
3	14.2 ± 3.5a	9.8 ± 5.4a
4	9.8 ± 2.6a	5.7 ± 3.8a
5	13.1 ± 4.8a	5.9 ± 4.7b

^{a/} Means followed by a common letter horizontally do not differ ($P = 0.05$).

^{b/} Days post treatment.

3) Fecundity. - The purpose of this portion of this study was to determine a dosage that would produce a chronic and a sublethal effect that might result in the weakening of the host. Consequently, such an effect may cause a general disruption of the vital functions which could be manifested in reduced reproductive potential and shortened longevity (Gaugler and Brooks 1975). However, it was difficult to achieve such a sublethal dose. We tried various spore

concentrations (6.3 to 38.1 spore/mm²) as measured by the amount of time larvae were exposed (Vandenberg and Soper 1979) but we were unable to obtain sufficient number of adults for fecundity study due to low rate of emergence even though in some of the treatments (lower dosages) there was a high percent of pupation. Table 8 summarizes the results from one of the successful tests. In the fungus treated group the mortality was 55.6 and 63.2% in male and female respectively. Weight of control pupae was 75.2 ± 1.6 mg in males and 111.4 ± 2.6 mg in females as compared to 59.7 ± 2.0 mg for males and 97.7 ± 2.0 mg for females in the treated group. Fecundity expressed as mean number of egg/female was 92.8 in the control (9 pairs) and 59.0 in the treated group (2 pairs only).

Vandenberg and Soper (1979) showed that mortality of larvae of the spruce budworm treated with *Erynia radicans* occurred in 3 to 6 days. Similarly, in our study larval death occurred in 4-6 days. During the infection stage, in this study, the food consumption and utilization were significantly lowered in the fungus treated larvae as compared with the control on day 4 and 5. Also, pupae from infected larvae weighed less than untreated ones. Such effects are probably a result of depleted nutritional reserves and a reduced ability to assimilate food efficiently (Thomson 1958). Consequently, larvae will be less efficient at forming nutrient reserves for the pupae and adult stages.

In insect species such as the spruce budworm, where the adults do not consume food, nutritional reserves are dependent on the amount of nutrients accumulated by the larvae for the entire metabolism of the individual (Jasic 1961). Thus, if the reduction in food consumption and utilization in infected larvae occurs under natural conditions, adult females arising from diseased larvae will have even smaller reserves, since the individual must use a portion of the fat stored for general activity, thereby diverting a large portion of this reserve from egg production. This is important when considering the utilization of *E. radicans* in the management of an insect pest like the spruce budworm in a forest situation where the foliage can tolerate some feeding without serious economic damage.

Table 8. - The effect of Eyrinia radicans on the spruce budworm larval mortality, pupation, emergence and fecundity.^a

Treatments	% Larval Mortality		% Pupation		Pupal wt (mg)		% Emergence		Eggs/per Female
	M	F	M	F	M	F	M	F	
Fungus treated	55.6	63.2	44.4	36.8	59.7 ± 2.0	87.7 ± 2.0	9.4	8.0	59.0
Control	0.0	0.0	100.0	100.0	75.2 ± 1.6	111.4 ± 2.6	98.0	100.0	92.8

^aRate of larval spore exposure was estimated at 8.4 spore/mm².

Based on the mean of only 2 pairs in the fungus treated group and 9 pairs in the control.

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RECENT FIELD STUDIES ON THE USE OF BACILLUS
THURINGIENSIS TO CONTROL THE GYPSY MOTH
(LYMANTRIA DISPAR L.)

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Efforts to improve the effective use of B. thuringiensis and reduce its application costs has stimulated the development of higher potency formulation. Recent field studies have shown that a single application at 30 BIU/ha (12 BIU/acre) is as effective as the split double application of 20 BIU/ha (8 BIU/acre) formerly recommended. Also results of using volumetric application rates of less than 9.6 L/ha (gallon/acre) are discussed.

Results of early studies on the field use of Bacillus thuringiensis (Bt) against the gypsy moth were encouraging but inconsistent. Aerial applications were often aggravated by incompatibility of Bt with its suspending medium (fuel oil) which often resulted in clogged nozzles and uneven spray coverage (Lewis and Connola, 1966). Development of standardization procedures based on insecticidal activity (Burgess et al. 1967, Dulmage et al. 1971), formulation improvements, and the isolation and development of better and more potent Bt strains such as the HD-1 strain (Dulmage, 1970) all contributed to the resolution of difficulties associated with the Bt product and its application. Field studies that were done with these newer formulations (Thuricide 16B, Dipel WP, Dipel 4L) prepared with the HD-1 strain showed that Bt could be applied aerially to protect the foliage and reduce the density of the pest populations (Dubois and Lewis, 1981).

Until recently the recommended procedure for aerial use of Bt to control the gypsy moth was two applications, each at 20 BIU/hectare (8 BIU/acre) sprayed at cre/ a volumetric rate of 9.5 to 19 liters per hectare (1 to 2 gallons per acre). The first application was made when oak foliage expansion was about 50% and the majority of the larvae were still in the first instar. This treatment was repeated 7-10 days later when most of the larvae matured to second and third instar (Yendol et al. 1973, Lewis et al. 1974). Unfortunately the high cost of both the double application and the product itself discouraged general and large-scale use of Bt even in environmentally sensitive areas.

Two improvements of Bt products are contributing to the renewed interest for general and large-scale use of Bt; one, newer formulations are several times more potent and have longer residual activity than previously available; two, new strains of Bt that are significantly more potent than the HD-1 strain are continually being uncovered and evaluated for commercial development. It is becoming

increasingly clear that as more and more strains of Bt are isolated, some are found to be more potent than the HD-1 strain against specific insect pests including forest and ornamental tree pests, agricultural pests, as well as disease vectors (Dulmage, et al., 1981).

Several studies were reported on the successful use of a single application of Bt compared to two applications previously recommended for use against the gypsy moth and spruce budworm (Morris et al., 1982, Morris, 1983, Reardon et al., 1982). Against the gypsy moth in particular, studies by different investigators (Table 1) have confirmed that one application at 30 BIU/hectare (12 BIU/acre) compared favorably to two applications at 20 BIU/hectare (8 BIU/acre). Regardless of the manufacturer or the formulation used (water or oil based), better foliage protection was achieved when Bt was applied once at the 30 BIU/hectare rate than when applied twice at/or lower than 20 BIU/hectare.

Table 1. Summary of Bacillus thuringiensis aerial spray tests conducted in Pennsylvania, Massachusetts and Connecticut comparing the effectiveness of single and double applications against instar II gypsy moth.

Applic. Rate	No. of Applic.	Popul. Trend	% Final Defol.	Ref.
10 ^{c/}	1	1.55 R	25	McLane and Finney (1982)
10	2	1.10 R	41	
20	1	1.30 R	42	
20	2	1.38 R	38	
30	1	1.12 D	8	
30	2	1.60 D	5	
Control	-	1.75 R	70	Andreadis et al. (1982)
20 ^{d/}	1	13.30 D	37	
20	2	15.00 D	15	
Control	-	6.50 D	61	
20 ^{a/}	2	975.30 D ^{e/}	3.7	Andreadis et al. (1983)
30	1	21.30 D	5.6	
40	1	13.10 D	7.6	
Control	-	23.70 D	72.3	

a/ rate of BIU applied at 9.5 liters per hectare

b/ ratio of egg mass change: $\frac{\text{Post spray}}{\text{Pre spray}}$ R = Rising population; $\frac{\text{Pre spray}}{\text{Post spray}}$ D = declining population

c/ Thuricide 16B (Zoecon, Inc.)

d,e/ Dipel 4L (Abbot Laboratories)

e/ Because of extreme variability, ratio is not significantly different from others.

In areas where the populations were on the decline, the trend was somewhat accelerated. Noteworthy is that in areas where populations were rising use of the single 30 BIU/hectare application rate reversed that trend and actually showed a decline in the egg mass change. Generally in these studies significant differences in relative larval densities were observed between treated and untreated blocks but differences between treatments were not significant. Furthermore, McLane and Finney

(1981) also showed that stickers effectively improved the residual activity of the *Bt* formulations. Eight days after application as much as 80% of the original insecticidal activity was retained on the sprayed foliage when acrylamide type stickers were incorporated into either oil or water based formulations. Without stickers insecticidal activity was reduced to 10 to 25% of its original activity. Undoubtedly the extended activity and improved physical formulation characteristics of these newer formulations contributed to the success of reducing application costs by eliminating the need for a second application. Slippey (1983) also reported that in declining populations, 30 BIU/hectare applications was as effective as higher dose rates (40 BIU/hectare) but when used against rising populations, results at 30 BIU/hectare were inconsistent.

Newer formulations of *Bt* designed for low volume application rates are from two to four times more concentrated than previously available. Such concentrated formulations contain from 12.7 to 16.7 BIU/liter (48 to 64 BIU/gallon) and permit the application of the 30 BIU/hectare rate at reduced volumetric rates. Against the spruce budworm, Dimond (1982) demonstrated that at 30 BIU/hectare, *Bt* could be used successfully at volumetric rates as low as 2.9 liters hectare (32 oz/acre). McLane and Finney (1982) reported that the same 30 BIU/hectare dose could be applied at a volumetric rate of 4.75 liters per hectare (64 oz/acre) against the gypsy moth and still provide excellent foliage protection and population reduction. Balaam (1983) also reported similar success of reduced volumetric rates at the same dose rate against gypsy moth infestations in New Jersey. The successful use of a single application of 30 BIU/hectare to control the gypsy moth must be applied when larvae are still in the second instar stage. Applications that are delayed until larvae are fourth instar will not be effective at 30 BIU/hectare. Higher dose rates of 40 to 50 BIU/hectare (16 to 20 BIU/acre) will only have a limited effect on the pest population (McLane et al., 1983).

Efforts to improve *Bt* formulations also include the development and evaluation of new strains. Andreadis and others (Andreadis et al., 1982) reported on the field evaluation of two experimental strains against a gypsy moth infestation. The strains, HD-243 and HD-263, were as efficacious as the commercially developed HD-1 as measured by relative larval densities and foliage protection. Noteworthy is that HD-243 was actually applied at half the dose rate of HD-1. Laboratory studies (Dubois unpublished data) had shown that HD-243 was about twice as potent as HD-1.

Recently a new strain of *Bt* labelled NRD-12 was isolated, which shows considerable promise for operation use (Dubois unpublished data). In a recent field study against a spruce budworm infestation it was significantly more effective than Thuricide® 32 LV. Both final defoliation estimates (12%) and the residual larval

population (3.2 larvae per 45 cm branch tip) present in the block treated with SAN 415¹ were significantly lower than in the Thuricide® 32 LV treated block (25% and 7 larvae per branch tip) when both formulations were applied at 30 BIU per branch hectare. Laboratory studies of the SAN 415 formulation also show that NRD-12 may be more effective than the HD-1 strain against the gypsy moth. Results of parallel bioassays (Table 2) show the SAN 415 32 LV is 3.9 times more potent than Thuricide® 32 LV. Both strains were formulated at the same potency of 8.5 BIU per liter (Thuricide® 32 LV BIU per gallon). Whether this increased effectiveness will also be apparent under field operational conditions remains to be confirmed.

Table 2. Laboratory bioassays^{a/} comparing HD-1 (Thuricide® 32 LV) and NRD-12 (SAN 415 32 LV) formulations against instar II gypsy moth.

	SAN 415 32 LV	Thuricide® 32 LV
<i>Bt</i> strain	NRD-12	HD-1
Serovar	H _{3ab}	H _{3ab}
Slope	5.37	3.73
S.E. ^{b/}	0.60	0.15
C.V. ^{c/}	0.19	0.07
LC ₅₀ (IU/ml)	45.20	173.7
S.E.	3.82	10.97
C.V.	0.15	0.11
Ratio ^{d/}	3.86	--

^{a/} average of 3 bioassays

^{b/} standard error

^{c/} C.V. coefficient of variation

^{d/} ratio of LC₅₀ of Thuricide® 32 LV to SAN 415 32 LV

¹Commercial formulation based on the NRD-12 strain. Mention of a commercial product does not constitute an endorsement by the USDA-FS.

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INTERACTIONS BETWEEN MICROBIAL AGENTS AND GYPSY

MOTH PARASITES

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The parasite Cotesia melanoscelus attacks small gypsy moth larvae more successfully than large ones, and Bacillus thuringiensis retards the growth of caterpillars it does not kill. Together, both factors lead to higher parasitism by C. melanoscelus in areas sprayed with B. thuringiensis than elsewhere.

One of the major advantages of microbial agents over chemical insecticides is their specificity. They are usually benign to non-target organisms such as parasites and predators, and indeed many gypsy moth natural enemies are not harmed by treatments with microbial sprays. For instance, Dunbar et al. (1973) found that percent parasitism by a number of gypsy moth parasites was similar in check and Bacillus thuringiensis spray plots, and in another study the number of adult parasites caught in malaise traps during the year of treatment was usually the same in all plots (Reardon et al. 1979). However, in some cases parasite numbers were decreased by sprays. Reardon et al. (1979) and Andreadis et al. (1983) found that the pupal parasite, Brachymeria intermedia (Hymenoptera: Chalcididae), was not numerous in B. thuringiensis-treated areas. Ticehurst et al. (1982) showed that the tachinid parasites Compsilura concinnata and Blepharipa pratensis parasitized a lower percentage of gypsy moths in B. thuringiensis spray plots than in non-spray plots, and Kaya et al. (1974) noted that larvae of the predaceous beetle, Calosoma sycophanta, were less abundant in B. thuringiensis-treated as compared to untreated areas.

A decrease in parasite or predator populations in areas treated with a microbe does not necessarily mean that the agent has a direct effect on the natural enemy. Parasites and predators respond to host populations, which are generally different in treated and untreated plots. B. intermedia, for instance, seeks out high light intensities and so is usually most abundant in defoliated areas (Weseloh 1976b). Thus its numbers are often higher in check plots where most defoliation occurs. In field situations it is often not possible to tell whether the depressing effect of the agent is direct or indirect. Also, with one exception

(to be detailed later), no laboratory studies have described the specific interactions between the most widely used microbial agent, Bacillus thuringiensis, and gypsy moth natural enemies.

A few workers have studied interactions between natural enemies and the gypsy moth nuclear polyhedrosis virus. Capinera and Barbosa (1975) showed that adults of the predaceous carabid beetle, Calosoma sycophanta, could pass viable virus polyhedral inclusion bodies through their gut without evident harm, and so may be a useful vector of this pathogen. Similarly, Raimo et al. (1977) demonstrated that the braconid, Cotesia (Apanteles) melanoscelus, could transmit virus from caterpillar to caterpillar when its ovipositor became contaminated, either artificially or from attacking diseased hosts. However, C. melanoscelus tends to avoid ovipositing in moribund hosts (Versoi and Yendol 1982), possibly restricting its usefulness as a vector.

Because such studies have not been extensive it is difficult to generalize about the impact microbial agents have on gypsy moth natural enemies. However, there is one interaction involving B. thuringiensis and the parasite, C. melanoscelus, that has received a substantial research investment.

In the early 1970's a number of field tests demonstrated that C. melanoscelus impact was enhanced in areas sprayed with B. thuringiensis. For example, in a 1972 spray test in Connecticut percent parasitism of field-collected caterpillars by C. melanoscelus averaged 1.0% in check plots and over 12 times higher (13.3%) in plots sprayed with Thuricide HPC or the experimental preparation IMC 90012 (Dunbar et al. 1973). The following year percent parasitism was 1.3, 7.0, and 20.6% respectively in check, Thuricide-16B, and Dipel WP plots. Also, an average of only 0.8 C. melanoscelus overwintering cocoons was located under each burlap band in check plots as compared to 4.7 in Thuricide and 8.1 in Dipel plots (Kaya, et al. 1974). Thus, the absolute number of parasite progeny as well as the proportion of hosts attacked increased in test plots. This is important because percent parasitism can be expected to increase in treated areas (assuming the disease has no direct effect on the parasite) even if parasites are not enhanced because low host numbers resulting from disease-induced mortality may result in a more favorable parasite:host ratio. Wollam and Yendol (1976) showed that this enhanced effect also occurred when 1000 mated female C. melanoscelus were released into plots which were also treated with Thuricide-16B. Counts of gypsy moth larvae under burlap bands as well as defoliation estimates were lower in plots receiving microbe and parasite than in plots receiving B. thuringiensis alone, C. melanoscelus alone or no treatments. This is the only study I know of where parasite releases

have been shown to actually reduce gypsy moth populations. It may be important that the effect occurred only when parasites were released in combination with B. thuringiensis.

The above reports show the potential which B. thuringiensis has for improving the effectiveness of C. melanoscelus. Because the combined effect was greater than the summed effect when either agent was present alone the phenomenon was a case of true synergism. Initially the causal mechanism was unknown. In early tests molasses was often used as an adjuvant in spray mixtures and may have attracted C. melanoscelus into the area. However, other parasites which should have responded to the molasses did not. Furthermore, I could not increase parasite activity by spraying from the ground with molasses. A clue to the mechanism involved occurred in the mid 1970's when I related C. melanoscelus parasitism rates to gypsy moth larval development (Weseloh 1976a). Percent parasitism by C. melanoscelus reached a peak when most hosts were in the second instar and declined thereafter, despite the fact that the parasite has two generations a year. First generation parasites emerge from overwintering cocoons when gypsy moth eggs are hatching and attack first instars. Their progeny develop without diapause and attack third and fourth instars. Clearly the first generation parasitized the most hosts in spite of the relatively large numbers of second generation adult parasites (as measured by sticky-panel catches) present when gypsy moths were fourth instars and larger. Results suggested that parasites did not successfully attack large caterpillars, and this was confirmed in laboratory tests. Because of the vigorous defensive movements and long hairs of older hosts, third and fourth instars were less frequently parasitized than were younger caterpillars (Weseloh 1976a).

I did not relate these results to the parasite-B. thuringiensis interaction until Ticehurst et al. (1982) found that, in addition to the increased parasitism by C. melanoscelus which occurred in Dipel-treated plots (32.3%, as opposed to 4.4% in the check plots), Dipel caused a one-week lag in development of surviving gypsy moths as determined by the appearance of pupae and adult moths. A similar lag was documented by Andreadis et al. (1983). This lag was caused by the gut-paralyzing effect of the delta-endotoxin of B. thuringiensis, which causes caterpillars to stop feeding at least temporarily (Heimpel and Angus 1959). Ticehurst, et al. (1982) suggested that this retarded development might enable C. melanoscelus to attack the small hosts it can successfully attack for a longer time, thus improving its effectiveness.

Laboratory work was done to investigate this. Ahmad et al. (1978) showed that B. thuringiensis-related mortality of larvae

parasitized with C. melanoscelus was similar to that of non-parasitized gypsy moths, and they also concluded that there was no evidence for a direct, toxic effect of B. thuringiensis on the parasite. Weseloh and Andreadis (1982) confirmed these results and also showed that surviving, B. thuringiensis-treated second instars were retarded in development about two days as compared to controls. When presented with untreated larvae of the same chronological age as larvae exposed to B. thuringiensis three days before, female parasites attacked both hosts equally. However, if B. thuringiensis exposure had occurred ten days previously, untreated hosts were attacked substantially less frequently than treated ones. Ten days after treatment 97% of the treated larvae were still third instars while only 60% of the healthy ones were, so the former were noticeably smaller than the latter. More importantly, a significantly greater number of parasites were reared from treated larvae than from untreated ones. Thus retarded development caused by B. thuringiensis is a plausible mechanism for enhancing the effectiveness of C. melanoscelus.

To test this hypothesis, C. melanoscelus and gypsy moth larvae were sampled in a 1981 aerial spray test using Dipel 4-L (Weseloh et al. 1983). As in the other tests mentioned, C. melanoscelus parasitism was only 1.2% in check plots and 6 to 12 times higher (6.9-14.8%) in treatment plots. Also, numbers of parasite cocoons under burlap flaps averaged only 4.0 per flap in control areas and from 13.2-20.3 per flap in treated plots. Caterpillar numbers were greatest and caterpillars were largest in the check plots. On June 11, only 5.2% of larvae were still third instars in the check areas, whereas 22% to 49% were third instars or smaller in treatment plots. Simple and multiple linear regression analysis clearly showed that percent parasitism was more closely related to the average caterpillar size per plot than to caterpillar numbers. This last point is important because, together with the larger numbers of parasite cocoons in spray plots, it shows that the increased parasitization was not due solely to changes in parasite:host ratios. Along with laboratory experiments, the test proved that the rate of gypsy moth development is critical to the field effectiveness of C. melanoscelus.

The importance of retarded host growth in improving the efficiency of C. melanoscelus led me to explore other circumstances where caterpillar development could be influenced. For instance, it is conceivable that low B. thuringiensis doses, lower even than those which cause mortality, might still retard caterpillar development. Also, feeding deterrents, by temporarily stopping feeding, might also be effective. In their field test Ticehurst et al. (1982) used Dipel 4-L at one-half the usual rate, but this still caused substantial mortality and no lower concentrations have to my knowledge been tested. Accordingly, in 1981 and

1983 I sprayed individual apple trees with B. thuringiensis concentrations ranging from the usual dose of 0.84 BIU to 0.035 BIU per tree (Weseloh, manuscript submitted). Other trees were sprayed with the miticide Plictran (tricyclohexylhydroxystannane), an antifeedant for gypsy moths (Meisner and Skatulla 1975). Plictran is registered for use on apples, and was applied at the recommended rate of 0.22 g/l active ingredient.

Larval numbers were reduced below controls for all B. thuringiensis rates of 0.21 BIU per tree or more, but only for the highest dose was defoliation reduced. Plictran did not decrease larval numbers, but it and all the B. thuringiensis concentrations significantly retarded caterpillar development. Attempts to monitor parasitism in these areas were not successful in 1981 because of extensive inter-tree movement of caterpillars and in 1983 because parasitism levels, in general, were very low. But the link between developmental rates of gypsy moths in the field and parasitism by C. melanoscelus has already been proved, so it is likely that if parasite activity could have been monitored it would have been increased by the treatments.

Interactions between B. thuringiensis and parasites is not restricted to C. melanoscelus. Wallner et al. (1983) found in a laboratory study that retarded development of gypsy moths caused by B. thuringiensis enhanced parasitism by an exotic braconid, Rogas lymantriae, although a higher proportion of males emerged from infected larvae than from healthy ones. Also, Hamel (1977) showed that percent parasitism by two parasites of the western spruce budworm, Choristoneura occidentalis, increased in areas sprayed with B. thuringiensis. The two parasites, Apanteles fumiferanae and Glypta fumiferanae, attacked pre-diapausing budworms before sprays were applied. Parasitized larvae did not eat as much as healthy ones, and so probably avoided ingesting lethal amounts of B. thuringiensis. This is a different mechanism than operates with the gypsy moth parasites, where it is parasitism occurring after spray application that is enhanced.

Natural enemies may frequently be enhanced by applications of microbial agents, although few studies have been reported. Clearly, this is an area of research that needs more emphasis. Chemical pesticides might have similar effects, but chemical pesticides usually lack the specificity of microbial agents and kill natural enemies along with the target pest. Looking for side effects of pathogens on hosts could be important because such side effects can profoundly influence the effectiveness of natural enemies.

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GYPCHek®: PAST AND FUTURE STRATEGIES FOR USE

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The development of the gypsy moth nucleopolyhedrosis virus product Gypchek, and strategies for its use, have been largely patterned after conventional pesticide technology. Prior to Gypchek registration with the Environmental Protection Agency in 1978, several field tests involving variations in virus product, application hardware, dose rates, timing and formulation were conducted. Further tests since 1978 have been promising, but nonconclusive, and 6 years after registration, Gypchek is not in commercial production. It is clear that if this product is to be seriously considered as either an alternative or adjunct to other control tactics, it must either be formulated in such a manner as to extend or amplify its activity on foliage, or it must be genetically manipulated to enhance its virulence.

As early as 1911, Reiff speculated that gypsy moth nucleopolyhedrosis virus (NPV) could be used to control the pest and some early field studies by Glaser and Chapman (1913) demonstrated its potential. In 1978 Reiff's prophecy was partially fulfilled with the EPA sanctioned registration of a gypsy moth NPV product Gypchek. This product was the fruit of several years of intense interdisciplinary research that ranged from understanding viral biochemistry and mode of action to testing and modifying viral delivery systems. The registration process has been bittersweet. A product that has great potential in gypsy moth management has been brought forward, yet in 1984, six years after registration, is not in commercial production. Why? The reasons will emerge as a brief chronology of Gypchek development and use are presented here.

Forest Service research on gypsy moth NPV began at the Northeastern Forest Experiment Station's Laboratory in New Haven, Connecticut in the early 1950's. A few, very limited field experiments¹ were conducted on individual gypsy moth infested trees treated with aqueous suspensions of macerated, virus-killed gypsy moth larvae. Results of these early studies were encouraging enough to test the virus in combination with *Bacillus thuringiensis* (B.t.) in a series of field trials in New York State, 1961-1963 (Lewis and Connola 1966). Virus used in these tests was from field collected (Connecticut) cadavers processed according to

Rollinson and Lewis (1962). Since NPV was not used alone, these tests were ostensibly undertaken more for the hope of augmenting B.t. mortality than for assessing the efficacy of NPV. Results of these field tests, though showing some NPV effectiveness, were compromised by B.t. formulation and application problems, which made the evaluation of NPV effects even more difficult. What became apparent after 3 years of this type of testing was that B.t., in the same tank mix and sprayed at the same time as NPV, was antagonistic to the NPV infection process through its own mode of action, i.e., feeding inhibition through gut paralysis. Since NPV must be ingested to cause mortality, any feeding inhibitors in its formulation clearly reduce its effectiveness.

In 1963, NPV was tested alone on a 1-acre (0.4 ha) plot of mixed oak in the White Memorial Forest, Litchfield, Connecticut (Rollinson *et al.* 1965). Virus used was again from Connecticut field-collected cadavers (Rollinson and Lewis 1962) and was applied by truck-mounted mist blower at a rate of 4×10^{12} polyhedral inclusion bodies (PIB) in 4 gallons (15 l) of water-sticker tank mix per acre. Although data from this test is sketchy, it is apparent that the NPV was effective in reducing gypsy moth populations in the treatment plot; 96 percent egg mass (EM) reduction. No pretreatment EM counts were given for control plots whose post-treatment EM densities were 5 fold higher than those in the treatment plot. Results of this test were instrumental in securing a Forest Service research commitment toward developing gypsy moth NPV as a microbial insecticide.

From these early field tests and from a variety of laboratory studies conducted on gypsy moth NPV and other insect viruses that followed, it became clear that first, gypsy moth NPV was not one of the more virulent insect viruses and second, that it remained active for only a few days following foliar application (Yendol and Hamlen 1973, Lewis and Yendol 1981). The implications of these findings relative to the development of Gypchek have been discussed in detail elsewhere (Lewis, 1981, Podgwaite 1984) but briefly, research focused on finding the most virulent gypsy moth NPV (the Connecticut strain, to date), developing a cost effective NPV production system (Shapiro *et al.* 1981), and finally developing a tank mix with sunlight protective properties.

By 1972 research had progressed to the point where further field testing was appropriate. A series of aerial tests were conducted in Pennsylvania between 1973 and 1978, the eventual year of Gypchek registration (Yendol *et al.* 1977, Wollam *et al.* 1978, Lewis *et al.* 1979). These field experiments evaluated various combinations of (1) a variety of NPV formulations (2) high versus low dose rates (3) one versus two applications (4) a variety of stickers, sunlight protectants and feeding stimulants (5) flatfan versus motorized nozzling systems and (6) morning versus evening application; all against a range of moderate to dense gypsy moth populations.

From an evaluation of all these tests emerged the current direct suppression tactic with Gypchek, i.e., two aerial applications, 7-10

¹F. B. Lewis, Personal Communication

days apart, each at a prescribed rate between 1.0 and 5.0×10^{11} PIB per acre, against second stage gypsy moth larvae within moderately dense gypsy moth populations. The tank mix should include an appropriate sunlight-screen and sticker. Under optimal conditions, expected results using this tactic are (1) 50-80 percent EM reduction (2) < 55 percent defoliation and (3) the prevention of refoliation.

Results of further field tests² in Connecticut in 1981, using Gypchek in 4L[®] as well as in Protec[®], although promising, were inconclusive. However, an aerial field test in Canada in 1982, using virtually the same Gypchek-4L formulation used in Connecticut in 1981, provided 95 and 90 percent EM reduction in treated plots compared to a 55 percent reduction and a 324 percent increase in EM in control plots. Treated plots averaged 20 percent defoliation compared to 45 percent for controls (Meating *et al.* 1983).

It is clear that there are some problems with Gypchek itself, as well as how it has been perceived, that have retarded its commercialization and its widespread acceptance as a microbial insecticide. The first is virulence. As mentioned earlier, gypsy moth NPV is of relatively low virulence when compared to several other insect viruses, e.g., the sawfly NPVs, many of which are 100 times as virulent against their respective hosts. Secondly, again reiterating, gypsy moth NPV is rapidly inactivated on foliage, losing most of its pesticidal activity within 2-3 days after treatment. Thirdly, erratic results from year to year, often due to the factors cited above, have done little to convince the user of its efficacy. Further, though the product is pesticidal only for the gypsy moth, and ultimately environmentally desirable, commercial producers are interested in developing products that will satisfy a broad market and to date have been hesitant to commit substantive resources toward developing products that will be used against only one insect. Finally, the users generally equate the performance of Gypchek with that of chemicals -- they expect equivalent results. Of course this is rarely achieved, and should not be expected. The product is essentially alive, requires 10-14 days to kill and has a narrow target window. It is unrealistic to equate its performance with a contact insecticide! The future of this product will hinge on its promotion as an adjunct to, rather than a substitute for, other pesticidal agents.

Toward this end some probing studies on alternate uses of this virus have been conducted. Parasite-NPV combinations have shown some promise. Raimo and Reardon (1981) found that the release of NPV-contaminated *Apanteles melanocelus* females resulted in almost double the incidence of NPV larval mortality in treated blocks compared to

controls, while percentage parasitism was virtually the same in both. Podgwaite *et al.* (1981) introduced gypsy moth NPV into sparse gypsy moth populations by treating egg masses. In addition to an estimated 85-90 percent NPV mortality in larva hatching from EM so-treated, there was a 20 percent incidence of polyhedrosis in 4th-6th stage larvae in the year of treatment.

There are other researchable control tactics with Gypchek. These include (1) its use in sequence with other control techniques, e.g., with B.t., parasites, pheromones, sterile male moth release, and chemicals (2) the release of NPV-infected larvae into populations free of the disease (3) the release of NPV-contaminated predacious insects, mammals and birds (4) the use of attractants to lure larvae to contaminated baits and (5) the spot inoculation of this virus early in the developmental cycle of the gypsy moth or in its preceding generation.

Gypchek is at a crossroad in its development as a microbial insecticide. It is clear that if this product is to be seriously considered as an alternative to chemicals in any control strategy that involves broadcast application, then either it must be formulated in a manner that significantly extends its activity on foliage, or the virus must be manipulated genetically to enhance its virulence or perhaps increase its host range to make it more attractive for commercial development. This can be realized through a systematic research effort in the area of formulation and application, while integrating state of the art biotechnology into fundamental research on gypsy moth NPV.

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RECENT FIELD RESEARCH USING MICROBIAL

INSECTICIDES AGAINST GYPSY MOTH

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Field research since 1978 using different formulations, dosages, and spray volumes of *Bacillus thuringiensis* Berliner (Bt) against the gypsy moth are reviewed. Problems associated with inconsistent results are discussed, with an emphasis on timing of application. Recommendations for proper use of Bt are presented along with suggestions for further studies on the use of Gypchek and development of better spray technology for both Bt and Gypchek.

Introduction

Two microorganisms are frequently used against gypsy moth, *Lymantria dispar* L; *Bacillus thuringiensis* Berliner (Bt) and a nucleopolyhedrosis virus (NPV). Field trials and research experiences with Bt in the 1960's and 1970's were summarized and reviewed by Harper (1974), Dubois (1981) and Cibulsky (1982) and will not be covered in this paper. NPV research is still centered on formulation and increased potency. Although NPV (GYPCHEK®) became commercially available in 1983 through Reuter Laboratories, Inc., it has not been used in the field except in research or plot studies. Lewis et al. (1979) and Lewis (1981) reviewed research on NPV and more recent summaries can be found in the 1981 and 1982 National Gypsy Moth Review Proceedings and in Laboratory Reports from the USDA-APHIS Otis Methods Development Center. This paper will concentrate on the recent studies and field experiences with Bt used against the gypsy moth.

Review of Field Trials 1978-1983

1978 and 1979

In 1978 and 1979 Bt was used operationally in suppression programs in only a few northeastern states. The two major Bt formulations applied aerially against the gypsy moth were Thuricide 16B® and Dipel-WP®. Most states relied on chemical insecticides, such as SEVIN® and Dylox®, to combat the gypsy moth because Bt was still trying to overcome its reputation as an environmentally desirable insecticide that produced inconsistent results. Field studies were conducted in New Jersey (McLane and Finney 1979) and New York (Abrahamson et al. 1981) with Thuricide 16B or 24B and results compared favorably with chemical insecticides in some cases and

poorly in other cases. In New York State, where Bt was used operationally in several counties, it was applied at 8 BIU's/acre in a spray volume of 128 oz. Half of the treatment blocks were treated with a second application. Control was marginal when compared to results using chemical insecticides. Improper timing of application, poor weather conditions, lack of knowledge by spray applicators in the use of biological insecticides, inadequate mixing equipment and inconsistent spray deposition and droplet size were all factors that contributed to Bt's poor performance (Abrahamson et al. 1981).

1980

The gypsy moth defoliated over 5.1 million acres in the northeast during 1980. Spray acreage increased dramatically in all affected states, and the need for environmentally safe and effective insecticides intensified. Improved formulations of Bt were developed and tested. Wettable powders were no longer desirable and formulations of Dipel 4L, Thuricide 32B and/or Thuricide 16B were field tested in Massachusetts and Rhode Island (McLane and Finney 1980), New York (Abrahamson et al. 1981) and Pennsylvania (Fusco 1982a). Rates were still 8 or 8 + 8 BIU's/acre in a spray volume of 128 oz except for one test at 32 oz/acre. Foliage protection and reduction in larval and egg mass densities were satisfactory in many cases, however results were not always consistent and in some cases exceptionally poor. Again, the reasons for poor results could be attributed to a number of factors, the most common being improper timing of the application. Once the gypsy moth larval population reached late 3rd and early 4th instars the effectiveness of Bt diminished dramatically. It also became more apparent in 1980 that spray equipment, such as aircraft/nozzle configurations and mixing apparatus, and weather conditions played an important role in spray coverage and program results. Uniform spray deposition (20-25 drops/cm²) and droplet sizes in the 100-200 micron range are necessary in order for Bt to control gypsy moth populations and/or protect foliage.

1981

Gypsy moth defoliation exceeded 13 million acres in 1981 and chemical insecticides were heavily used throughout the northeast. However, Thuricide 16B or Dipel 4L was used operationally in New Jersey, New York, Pennsylvania, Massachusetts and Maine. Bt use increased, but again results against dense populations were inconsistent when compared to chemical insecticides. Research on population reduction and foliage protection were conducted in Massachusetts with Thuricide 16B and 32BX (Burnham 1981 and McLane and Finney 1981) and in Connecticut with Dipel 4L (Andreadis et al. 1982). In Pennsylvania a Bt-parasite interaction study with Dipel 4L was also conducted (Fusco 1982b and 1982c). The above studies used the 8 or 8 + 8 BIU/acre rate in 128 oz spray volume applied aerially except

in Massachusetts where one and two applications of 4 and 12 BIU's/acre were also evaluated. One ground application study also occurred in Connecticut with Dipel 4L at the 8 BIU rate in a spray volume of 100 gallons/acre (Moore and Anderson 1982).

1982

Based on the results from 1980 and 1981, new concentrated formulations of Bt were developed for field testing in 1982 using higher BIU rates (12 and 16 BIU's/acre), and lower spray volumes (48 and 64 oz instead of 128 oz/acre). Tests were conducted in Connecticut with Dipel 4L at 8 + 8, 12 and 16 BIU's/acre in a spray volume of 128 oz (Andreadis et al. 1983); in Pennsylvania with Dipel 4L, Dipel 6L, Thuricide 32LV and Bactospeine at rates of 12, 12 + 12 or 16 BIU's/acre in spray volumes of 128 oz (64 oz for each of the 12 + 12 BIU/acre applications) (Fusco 1983a); in Pennsylvania by the USDA-APHIS with Dipel 4L, Dipel 6L, Thuricide 32LV and Thuricide 48B at rates of 8, 12 or 16 BIU's/acre in spray volumes of 48, 64 or 128 oz (McLane and Finney 1982); in New Jersey with Dipel 4L and Thuricide 32LV at the 12 BIU's/acre in a spray volume of 128 oz (Metterhouse and Balaam 1983a); in New York with Dipel 4L at 8 + 8 and 16 BIU's/acre in spray volumes of 128 oz (Glenister 1982) and a ground application study with Thuricide 32LV at the 12 BIU/acre rate in a spray volume of 100 gallons/acre (Eggen and Abrahamson 1983).

Overall results indicated that one application of these Bt formulations at 12 BIU's/acre in 128 oz spray volume provided foliage protection and reduced egg mass density in the spray blocks. The results from these studies set the stage in 1983 for a large scale suppression program in Pennsylvania with Bt.

1983

During 1983 a number of field studies were conducted throughout the northeast with different formulations of Bt at the 12, 16 or 20 BIU's/acre rate and a number of different spray volumes (24, 32, 48, 64 or 128 oz). These studies were conducted in New Jersey (Metterhouse and Balaam 1983b), Pennsylvania (McLane 1983, Fusco 1983b), and New York (Glenister 1983). Three Dipel formulations (4L, 6L and 8L), four Thuricide formulations (32LV, 48LV, 64LV and 64BX), Bactospeine and Futura were all field tested.

Operational programs using Bt in 1983 were conducted in Pennsylvania, New Jersey, Maryland and West Virginia. Thuricide 32LV, Dipel 4L or Dipel 6L at the 12 or 16 BIU's/acre rate in spray volumes of 64, 96 or 128 oz were evaluated.

The results from the field trials and operational programs indicated that when

properly applied, 12 BIU/acre (or higher) in 96 or 128 oz spray volume gave results that were comparable to those obtained with chemical insecticides. Rates lower than the 12 BIU rate or 96 oz spray volume/acre gave variable degrees of foliage protection and egg mass reduction depending on local gypsy moth conditions and other operational factors.

The overriding factor that affected results in these field trials and operational programs was timing of the application so that it coincided with the 2nd and 3rd instars of the gypsy moth. As soon as a majority of the larval population reached the late 3rd and the early 4th instars efficacy dropped dramatically. Application rates of 16 or 20 BIU's/acre provided somewhat better results against 4th instars, but against 2nd and 3rd instars the results were not different than those observed with the 12 BIU's/acre rate.

Conclusions and Recommendations

1. The number one factor to be considered and closely monitored in any spray program using Bt is the developmental stage of the gypsy moth. Bt must be applied after egg mass hatch is completed and larvae are in the 1st-3rd instars. Leaf expansion should be at a minimum of 20 percent. As soon as the gypsy moth reaches the late 3rd to early 4th instar, higher rates of Bt and/or a second application should be considered. If not, application of a chemical insecticide may be necessary.

2. A single application of Bt at 12 BIU's/acre is recommended for operational use in areas with a declining population, or in areas that have building populations with less than 1000 large egg masses per acre. Multiple applications of 12-20 BIU's/acre or switching to a chemical insecticide should be considered in areas with high building populations (> 1000 large egg masses per acre).

3. More studies should be done to evaluate Bt on a range of gypsy moth population densities using low spray volumes with improved aircraft/nozzle spray application systems, such as Micro-naire rotary atomizers, which give consistently uniform spray droplet sizes.

4. The newer Bt formulations are definitely better than the older formulations used in the 1960's and 1970's, and with improved application technology (stickers, nozzle types, spray equipment, etc.), results should be more consistent.

5. Research is continuing on newer and more potent Bt strains. The HD-1 strain now currently being used could be replaced by a more potent strain in the future.

6. NPV must be field tested more extensively in various formulations to determine its effectiveness against different population densities and to understand how this microbial can

best be incorporated into state IPM programs. All areas of spray technology must be studied with regard to NPV before it can be used on an operational level.

7. Additional research should be conducted on Bt-parasite interactions.

8. In large scale suppression programs, the effectiveness of a microbial insecticide depends on the amount of time, planning, manpower and monitoring that goes into the effort. The use of biological insecticides on an operational level requires proper application methods, otherwise the program is doomed to failure.

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SELECTION OF NEW MORE POTENT STRAINS OF BACILLUS
THURINGIENSIS FOR USE AGAINST GYPSY MOTH AND
SPRUCE BUDWORM

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The increased use of B. thuringiensis as an
alternative to chemical insecticides has
stimulated the search for more potent strains.
Presently over 1100 strains have been isolated
from worldwide sources. Some of these appear to
be more effective than the commercially developed
HD-1 strain against both the gypsy moth and
spruce budworm. One strain in particular, when
prepared as a standardized formulation was more
effective than HD-1 against the eastern spruce
budworm when compared under laboratory and field
operational conditions. Laboratory bioassay data
also indicates that against gypsy moth it may be
approximately four times more potent than HD-1.

The selection of new B. thuringiensis (Bt)
strains for development and use against specific
insect pests can be a difficult and confusing
task. The potency and toxin production of a
given strain can be directly affected by the
fermentation conditions used; not one single
fermentation condition will be ideal for all
isolates. Delta-endotoxins produced by different
strains can differ quantitatively and
qualitatively from each other and can have
different activity spectra against a particular
test insect. The spectrum of activity of a
particular strain against different insect
species, will vary such that a strain
particularly potent against one insect species is
not necessarily equally potent against another.
Each strain has to be evaluated against each
insect species.

Initial Studies: An understanding of the
activity spectrum of Bt requires the evaluation
of many strains against many different insect
species. Because no single laboratory has the
resources to conduct such an evaluation, several
scientists from different laboratories were
organized into the International Cooperative
Program on the Spectrum of Activity of Bacillus
thuringiensis (Dulmage 1979). It was through the
cooperation of this international program that
about 300 uniformly prepared strains of Bt were
recently evaluated against both the spruce
budworm and gypsy moth. The results of this
study will be reported here.

However, prior to this recent evaluation of
Bt strains against the gypsy moth and spruce
budworm the combined results of the first phase
of this international research study, which
included the screening of 350 strain preparations
of Bt against 23 insect species was published in
1981 (Dulmage et al. 1981). The general
conclusions were: (1) there is an

interrelationship between insecticidal activity
spectrum and strain serovar; (2) the same
delta-endotoxin (crystal) can be produced by
strains from more than one serovar; (3) clearly
serologically different delta-endotoxins
(crystals) i.e., K-1 and K-73, can be produced by
strains of the same serovar; (4) against specific
insect species some strains were more potent than
the commercially developed HD-1 strain.

Specifically, against the gypsy moth (Dubois
1984a), there is a closer relationship between
the crystal serotype and relative potency than
between serovar and relative potency.
Approximately 5% of the 350 strain preparations
that were screened were considered very potent,
and 16% were moderately potent. Of the 19
strains considered very potent 17 had a K-1 or
K-1+ mixed crystal serotype and one each had a
gal and aiz crystal serotype (from 64 and 35
representative strains respectively). Thirty
three of the 57 strains that were considered
moderately potent had a K-1 or K-1 + mixed
crystal type. The influence of the type of
crystal on potency can be particularly
appreciated when we consider that most of the
strains with a K-1 crystal type were of serovar
H_{3a} 3b var. kurstaki (49 strains), strains of the
same serovar that produced a K-73 type of crystal
(23 strains) were nonpotent or weakly potent.
Forty-five strains of serovar H₁ variety
thuringiensis that had a thu crystal type were
also screened; only 9 of these strains were
moderately potent and none were very potent.
Numerous strains representing other serovars were
also screened and most were weakly potent or
nonpotent.

Relative to Trichoplusia ni and Heliothis
virescens, strains that were very potent against
the gypsy moth had a Tn/Hv ratio of 1.91 which
is a good indication that potency is associated
with the K-1 type of crystal (Dulmage et al.
1981). Also strains that were very potent
against gypsy moth were also very potent against
T. ni but the reverse was not necessarily true.

The initial screening program identified
some Bt strains that were as potent or more
potent than HD-1 against specific insects. Two
of these strains were field tested against a
gypsy moth infestation and the results were
encouraging (Andreadis et al. 1982). Morris and
Moore (1983) evaluated 50 strains against spruce
budworm larvae. Their selection for evaluation
was based on the spectrum of activity of the
selected strains against the Douglas fir Tussock
Moth; none were more potent than the presently
commercially used HD-1 strain.

Current Studies: For the present study, the
LC₅₀ (in µg/ml of diet) of 298 uniformly prepared
strains was determined against both the gypsy
moth and spruce budworm. Additionally the LT₅₀
(at specific doses) of the experimental strains
against the spruce budworm was also determined.
The LC₅₀ (and LT₅₀) of the HD-1 International
Standard, HD-1S-1980, was determined against the
same batches of larvae and used to compare the
relative potency of the experimental strains.

The response of gypsy moth larvae to a
specific preparation of Bt is generally
consistent. Results of laboratory bioassays on

numerous batches of three generations of laboratory reared gypsy moth and spruce budworm larvae with the HD-1 standard, HD-1S-1980, are summarized in Table 1. The average LC_{50} is reasonably consistent between the generations (F_{23} to F_{25}) of gypsy moth that were used. Between batch and within generations variability (as measured by the C.V.) was higher than desirable but nonetheless acceptable. Slopes of the regression usually range between 4-5 ($P = 0.05$). Using the defined potency of 16,000 International Units of potency (IU)/milligram (mg) for the HD-1S-1980 standard, the overall LC_{50} for the three generations ranged from a low of 75 to a high of 105 IU/milliliter (ml) of diet. This is in good agreement with an earlier estimate of 96.2 ± 5.4 IU/ml (Yendol et al. 1973).

Table 1. Averages of the 1981, 1982, and 1983 bioassays with the standard HD-1S-1980 against laboratory stocks of instar II, Lymantria dispar L. and instar IV, Choristoneura fumiferana (Clem.)

Insect	YEAR		
	1981	1982	1983
<u>L. dispar</u>			
No. of bioassays	28	30	33
LC_{50} (μ g/ml of diet)	5.25	4.95	5.99
+ 95% C.L. ^{a/}	0.72	0.47	0.55
S.E. ^{b/}	0.35	0.23	0.27
C.V.	0.36	0.25	0.26
<u>C. fumiferana</u>			
No. of bioassays	6	18	22
LC_{50} (μ g/ml) of diet)	4.84	4.75	6.88
+ 95% C.L.	2.52	1.35	1.25
S.E.	0.98	0.64	0.60
C.V.	0.49	0.57	0.41

a/ C.L. - confidence limits

b/ S.E. - standard error

c/ C.V. - coefficient of variation

Mortality data obtained from spruce budworm bioassays is often heterogeneous. Frequently, variation about the LC_{50} results in wide fiducial intervals which can actually be understated and will limit meaningful interpretation of the potency of a particular test strain relative to the standard. As such, estimates of the LC_{50} of a particular preparation are usually discarded when the calculated "g" value exceeds 0.2 (Finney 1964). The mean LC_{50} over three generations of spruce budworm with HD-1S-1980 are also summarized in Table 1. Between generations, the LC_{50} is fairly consistent however between batch (within generation) variability can be large (note the high C.V.) such that, with all generations considered, the LC_{50} could actually range ($P = 0.05$) from 37 to 137 IU/ml of diet. Slopes of the regression usually vary between 2 and 3. Variability within and between bioassays with Bt against the spruce budworm has been a continuing problem for this and other investigators. Fast and Dimond (1984) and Fast and Régnière (1984) have reported higher LC_{50} and lower slope values in their bioassays with the HD-1 standard, HD-1S-1971 (precursor to

HD-1S-1980) than reported here with HD-1S-1980. Some of these discrepancies could be accounted for by differences in diet and larval rearing conditions and the bioassay procedure used. The observation that larvae recover after exposure to Bt and the possibility of cycling of feeding inhibition and recovery could also contribute to the variability observed in bioassays with this insect. These investigators also reported that there was no significant difference in susceptibility between instar IV to VI. On the other hand Dubois and Squires (1970) had reported that in gypsy moth the LC_{50} of a Bt preparation could vary with larval weight and age.

The LT_{50} of spruce budworm with HD-1S-1971 as reported by Fast and Régnière (1984) was also higher than reported here (Table 2). Their estimate did not vary with larval age but did vary with Bt dose and length of larval exposure on the test diet. Present estimates of the LT_{50} with HD-1S-1980 over a two-fold dose range against instar IV larvae is remarkably consistent and within dose variability is very low.

Table 2. LT_{50} of different doses of the HD-1 standard, HD-1S-1980, against instar IV Choristoneura fumiferana (Clem.)^{a/}

LT_{50} (days)	Dose in IU (μ g)/ml of diet		
	200(12.50)	150(9.38)	100(6.25)
	4.9	4.6	4.1
95% range	4.3-5.6	2.9-6.7	3.6-4.7
C.V.	.19	.30	.14

a/ Larvae in constant contact for 8 days; 16:8 L:D photo period, 21°C. Average of 8 bioassays/

Most of the 298 strains evaluated in the present study were weakly potent or had no effect on the hosts. None of the 18 strains of serovar H_{14} var. isrealensis or the 14 strains of serovar H_{10} var. darmstadiensis had any effect on these two insect species. Numerous other strains had a limited effect on larval growth and effected very low mortality even at doses as high as 100 μ g/ml of diet. Based on the response of these insects to the standard (Table 1) only those experimental strains with an LC_{50} of ≤ 1.99 μ g (32 IU)/ml and those with an LC_{50} between 2.00 and 10.00 μ g (32 and 160 IU)/ml of diet are summarized in Table 3; these LC_{50} values would indicate strains that are more potent than or equally potent as the HD-1S-1980 standard. The majority of the strains that are more potent than HD-1S-1980 against both insect species are primarily of serovar H_{3a3b} var. kurstaki and have a K-1 type crystal. A few strains of serovar H_{4a4c} var. kenyae and serovar H_7 var. aizawae are also very potent against both insect species. Of all the strains that are considered more potent than the standard against each insect species (16 + 10, $LC_{50} \leq 1.99$ μ g/ml) only four are equally more potent against both insect species. These are HD-262 (H_{3a-3b} -K-1), HD-545 (H_{3a3b} -K-1), HD-551 (H_{4a4c} -ken) and HD-562 (H_{3a3b} - ?). Against gypsy moth very

potent strains of other serovars worthy of mention are HD-287 (H_{5a5b} - K-1) and HD-854 (H_7 - ?) whereas against the spruce budworm HD-150 (H_{5a5b} - gal) and HD-120 (H_7 - K-1) are also worthy of mention as being specifically very potent. The observation that only four strains were equally very potent against both insect species and that there were a few strains uniquely potent against each insect further supports the observation made in the initial study that for each insect species there are some strains that are uniquely potent (Dulmage *et al.* 1981).

Table 3. Summary of the bioassay of HD strains considered more potent ($LC_{50} < 1.99 \mu\text{g/ml}$) or as potent ($LC_{50} \geq 2.00 < 10 \mu\text{g/ml}$) as the HD-1S-1980 standard against gypsy moth and spruce budworm.

serovar	crystal serovar	Gypsy moth		Spruce Budworm	
		$LC_{50} - (\mu\text{g/ml})$		$LC_{50} - (\mu\text{g/ml})$	
		< 1.99	≥ 2.00	< 1.99	≥ 2.00
		< 10.00		< 10.00	
1	thu	0	5	0	1
	K-1 +				
	thu	1	9	0	2
	K-1	1	2	1	0
	NI ^{a/}	0	0	0	1
3a	ale	0	0	0	1
3a3b	K-1	5	19	5	6
	K-73	0	1	0	0
	NI	1	6	2	0
4a4c	ken	2	1	1	3
	NI	1	1	0	1
5a5b	K-1	1	0	0	0
	gal	0	2	1	0
6 sub	sub	0	0	0	1
6 ent	ent	0	1	0	0
7	aiz	1	6	0	5
	NI	1	2	0	2
8a8b	K-1	0	1	0	0
	NI	1	0	0	0
9	tol	1	3	0	1
	NI	0	2	0	0
12	NI	0	1	0	0
Unk ^{b/}	thu + K-1	0	1	0	0
	aiz	0	1	0	0
	NI	0	4	0	1
Totals		16	68	10	25
Other Totals ^{a/}		214		263	

a/ not identified

b/ serovar not determined

c/ strains non/or weakly potent

In addition to the 298 strains of Bt reported above, twenty other strains of Bt were also evaluated. These strains were isolated (Dubois unpublished data) from diseased spruce budworm larvae received as hibernaculum from FPMI at Sault Ste. Marie, Ontario. No other shipment of larvae received from FPMI either prior to or since that particular shipment exhibited such a high natural incidence of Bt infection. All the strains that were isolated except for one, were identified as serovar H_{3a3b} var. *kurstaki*; one strain was identified as serovar H_{5a5b} var. *galleriae* (G. Donaldson USDA-ARS, Brownsville, TX 1983, personal communication). The serotype of the crystal of these new strain has not been

determined. Three of these isolates labelled as NRD-8, NRD-10, and NRD-12, are 2 and 3.5 times more potent than a similarly prepared HD-1 (concentrate or formulated) against the spruce budworm and gypsy moth respectively. Also, unique with these three strains was their rate of kill against the spruce budworm. Regardless of the preparation, spore-crystal concentrate or standardized formulation, the LT_{50} of the three strains was almost half that of a similarly prepared HD-1 or of the international standard, HD-1S-1980 when compared at similar doses of $\mu\text{g/ml}$ of diet. One of these strains, NRD-12, was commercially formulated and labelled as SAN 415 32LV. This formulation, standardized at 32 BIU/gallon, was then compared to the registered HD-1 formulation, Thuricide 32 LV[®], against a natural spruce budworm infestation. The favorable results were summarized in a preceding presentation (Dubois 1984b). The microbial and pathogenic characteristics of this strain are summarized in Table 4. The higher potency of NRD-12 compared to HD-1 is also apparent from bioassay with *H. virescens* but not with *T. ni*.

Table 4. Summary of the microbial and pathogenic characteristics of the NRD-12 *Bacillus thuringiensis* strain.

Source: Isolated by N.R. Dubois from diseased *Choristoneura fumiferana* (Clem.) larva at the NEFES-USFS laboratory at Hamden, CT, January 1981. Larva had been received from FPMI Sault Ste. Marie, Ontario in December 1980

USDA *Bacillus thuringiensis* Culture Collection No. for NRD-12 is HD-945. Serovar: H_{3a3b} variety *kurstaki*, crystal antigen unknown.

Bioassay Characteristics:

	Comparative Potency (IU/mg)		
	<i>Trichoplusia ni</i>	<i>Heliothis virescens</i>	
HD-1 R641A:	39,800	15,400	
NRD-12 (HD-945):	30,300±8980	32,700±7280	
<i>Lymantria dispar</i>	NRD-12 (conc.)	HD-1S-1980	Ratio
Slope:	5.19	3.75	
LC_{50} ($\mu\text{g/ml}$)	1.75	6.14	3.51
LC_{50} (IU/ml)	28.00	98.2	
<i>Choristoneura fumiferana</i>			
Slope:	2.85	3.50	
LC_{50} ($\mu\text{g/ml}$)	1.75	3.60	2.06
LT_{50} (days) (3.0 $\mu\text{g/ml}$)	4.6	8.3	1.80
(6.6 $\mu\text{g/ml}$)	2.7	5.1 ^{b/}	1.91

a/ Serovar, data for *T. ni* and *H. virescens* provided by G. Donaldson and H. Dulmage, USDA-ARS, Brownsville, TX.

b/ LT_{50} based on a spore-crystal concentrate of HD-1: for LT_{50} of HD-1S-1980 at comparable dose refer to Table 2.

This similarity to HD-1 relative to its serovar and its potency against *T. ni* was also independently confirmed by Hostetter (D. Hostetter, USDA-ARS Columbia, MO, personal communication Dec. 1983). However, its spectrum of activity (and presumably that of NRD-8 and NRD-10) relative to gypsy moth, spruce budworm and *H. virescens* certainly indicates some toxin composition different from HD-1. Furthermore, its rate of kill (LT_{50}) against the spruce budworm is significantly faster than with any preparation of HD-1 (at comparable doses) reported by others (Fast and Régnière 1984, Fast and Dimond 1984), or reported in this study. This insecticidal characteristic may be particularly advantageous in operational use of Bt (Fast and Dimond 1984, Morris, 1983).

Evaluation of Bt strains against insect pests is a continuing effort to search for new more effective strains. Presently, approximately 1,100 strains have been isolated from worldwide sources, and as with the NRD-series more are continually being isolated. This influx of new strains will undoubtedly increase as the potency of variants generated from genetic engineering efforts need to be evaluated.

Aside from the large grouping of the specific activity of serovar H₁₄ against mosquitos and black flies, differences in activity among lepidopteran pests are more subtle. These differences such as the LT₅₀ differences between NRD-12 and HD-1 relative to spruce budworm may have a greater impact on field effectiveness than the two-fold difference in LD₅₀. Whereas the almost four-fold difference in LD₅₀ of these two strains relative to gypsy moth may be the insecticidal characteristic of greater significance. These observations along with the results of this survey, that only four strains were equally very potent against both insects and several strains were uniquely very potent against each insect species certainly suggest that serious efforts to improve the use of Bt by strain selection will require the evaluation of each strain against each insect pest.

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Screening of 402 strains of more than 18 varieties of *Bacillus thuringiensis* showed chitinase to be inducible in virtually every serovar tested. Though the chitinase titre varied among strains, there was a strong correlation between enhanced lethality to spruce budworm, *Choristoneura fumiferana* (Clemens), and an increase in chitinase titre within the serovar. Strains grown in chitinase inducing medium gave a more rapid and higher kill than those grown in sporulation medium, and a faster kill than the currently used commercial strain.

Introduction

The sustained and growing assault on vast areas of spruce, balsam and Douglas fir forests by *Choristoneura fumiferana* (Clemens), the Spruce Budworm (SBW), has occasioned a variety of treatment regimens. Among these, and still representing an area of controversy, is the application of chitinase as an adjuvant in *Bacillus thuringiensis* (B.t.) treatments (Smirnoff 1974, 1977; Morris 1976). Indeed, little clear-cut evidence is available, at this time, on which to base a definitive opinion. Work in our laboratory (Dubois 1977; Daoust 1978) has demonstrated that the presence of microorganisms originally isolated from their insect host, induced in growth medium for chitinase production, and subsequently applied to leaf tissue, is associated with lesions produced in the peritrophic membrane of larvae which have ingested these chitinase active microorganisms. Ultimately, death occurs as a result of the generalized septicemia which follows spore and cell invasion through these perforations. Accordingly, it was decided to search among the various strains of B.t. for chitinase active cultivars. The underlying hypothesis was that such chitinase active organisms could, in hydrolyzing gut membranes, mediate spore entry and activity and, augmented by the activity of the crystal toxin on the epithelial cells of the gut, prove more lethal than non-chitinase active strains.

In the report which follows, we survey the incidence of chitinase activity in a wide range of B.t. crystal and serotypes, and indicate the relationship between chitinase activity, crystal type and lethal effectiveness to SBW.

Methods and Materials

Bacillus thuringiensis

Cultures of *Bacillus thuringiensis*, used in this study, were obtained from Dr. N. R. Dubois of the Center for Biological Control of the Northeastern Forest Experiment Station, U.S. Forest Service, Hamden, CT. These were maintained on nutrient agar slants and stored at 4°C until needed. The various B.t. cultures were tested for chitinolytic activity by streaking on petri plates containing a mineral salts medium as described by Dubois (1977) in which 0.1% purified chitin served as the sole source of carbon. Replicate plates containing 0.2% casamino acids as well as chitin, were streaked with B.t. to assess the effects of this enrichment on the growth of the organism. Chitinolytic activity was estimated from the degree of clearing around each colony at 4, 6 and 12 days after inoculation.

Strains of B.t. were tested quantitatively for chitinase production colorimetrically. Chitinase titers were measured by the addition of 0.5 ml of 0.1M citrate buffer (pH 5.0) and 0.5 ml purified colloidal chitin (25 mg/ml) to 0.5 ml of supernatant from each test culture. The supernatant was obtained by centrifuging the whole culture for 15 min at 10,000 rpm in an RC-2 Sorvall refrigerated centrifuge. Chitin, one batch used throughout, was purified as described by Daoust (1978); broth culture techniques are described below.

The assay mixtures were incubated for one hour at 50°C in a water bath. This temperature favors the action of the enzyme complex which attacks the chitin polymer, as opposed to those chitinase components which hydrolyze oligomer or dimer units (Weir 1978). Controls contained 0.5 ml distilled water instead of culture supernatant. Colorimetric determination of N-Acetyl D-glucosamine (NAG) levels, as a measure of chitinase titers, were made using a B & L Spectronic 21 colorimeter at 585 nm according to the method of Reissig *et al* (1955).

Cultures showing strong chitinolytic activity were selected for further testing in bioassays of SBW mortality. They were cultured in quantity using two media, one medium designed to amplify production of spores and crystals, and the other selected to enhance chitinase production while still permitting sporulation and crystal formation.

When maximal spore and crystal production was desired, flasks were prepared containing 100 ml of B.t. sporulation medium as described by Dubois (1968). Inocula were obtained from 24 hour cultures grown in trypticase soy broth (TSB), transferred again to TSB for 4-6 hours to obtain log phase growth and added as 1% of the volume of the medium in the sporulation growth flasks. These flasks were incubated at 27°C for 3 to 5 days on a shaker table. Cultures were then examined microscopically for the presence of spores and crystals and only cultures which contained both were used in bioassays. Acceptable levels were considered to be 90% spores and crystals as compared to vegetative cells, and a 1:1 ratio of spores to crystals was virtually always found.

B.t. cultures were also grown in a chitin based liquid medium designed to increase the chitinolytic activity of the bacteria. It contained the mineral salts trace elements present in the solid medium used in the agar plates, and 3% crude chitin as the sole source of carbon.

The chitin was obtained from Pfaltz and Bauer, Stamford, CT. A single batch of crude chitin from this source sufficed for all experiments described in this report. The crude chitin was boiled 10 min in distilled water, followed by 5-6 distilled water rinses. After each rinse, the chitin was allowed to settle and the water was decanted by suction. The cleaned chitin was dried in an oven at 30°C, and further ground for approximately 20 minutes (2-3 min pulses) in a blender.

TSB tubes (5 ml) were inoculated from slant cultures and incubated 20-24 hours at 25°C, after which 1 ml from the tubes was inoculated into 99 ml of mineral salts, 3.0% chitin broth in 250 ml flasks. The flasks were incubated at 27°C in the dark on a rotary shaker (115 oscillation/min).

Spruce Budworm

Cultures of *B.t.* were subsequently tested for virulence on SBW larvae which were reared as follows: hibernacula of SBW were obtained from the USDA Forest Service in Hamden, CT. and kept refrigerated. As needed, squares (approx. 1 cm²) of cheesecloth containing the hibernacula were cut and placed on the underside of the lids of 1 oz plastic cups. The cups were filled approximately 1 cm high with "Bio-Serv" SBW diet medium containing aureomycin (Bio-Serv, Inc., Frenchtown, N. J.). The medium, its water and agar components sterilized to reduce contamination, was poured at about 120°F, and allowed to solidify within the cups.

Cups were incubated at 25°C (approx. 70% relative humidity) in 24 hours of light a day for approximately 3 weeks, or until larvae had attained fourth instar. Cups were incubated in an inverted position to take advantage of the larvae's photopositive behavior and to reduce mold infection in the cups. Larvae were transferred to new cups if they became overcrowded, if the diet medium was depleted or dried out, or if mold began to grow on the medium. Larvae were discarded if they showed any signs of infection.

The eclosure of SBW larvae is not synchronous, and in fact may span a week. Consequently, the growth of the larger larvae in a group occasionally was slowed down by sequestering them in a 12°C incubator, permitting smaller larvae to catch up in size. Larvae in the three penultimate instars were used in bioassays. These larger larvae were separated into empty cups and starved for 24 hours at 12°C prior to each bioassay. No more than 5 larvae were placed in a cup to reduce cannibalism.

Larvae were then sorted for size and instar, and transferred to replicate groups of 7 comparable individuals into prepared bioassay dishes. The

bioassay dish consisted of an 8.5 cm plastic petri dish, floored with a piece of filter paper.

A small sprig of balsam fir was placed in each dish. Each sprig contained about 30 needles, and had a branch stem approximately 4 cm in length. In most experiments, the treatment to which the SBW larvae were subjected was applied on the surface of this balsam sprig.

For each treatment, balsam fir sprigs were washed in tap water, then dried at room temperature. Sprigs were next dipped into an aliquot of whole culture in beakers (usually 6 ml in a 25-50 ml beaker) followed by air drying for approximately one half hour. Triton X-100, a surfactant, was added at 0.1% to all treatments to enhance leaf wetting and adhesion by active agents.

Seven SBW larvae were added to each bioassay dish after a suitably prepared fir sprig was in place. They were allowed to feed (or not) on the sprig for 48 hours after which an untreated sprig replaced the treated one as a food source. Consumed sprigs were replaced as needed. Five to ten replicates of each dish were used, and controls dipped in sporulation medium or chitin broth were maintained. For most experiments, the number of viable bacteria (cells and spores), in the cultures employed was determined by the "drop plate technique" of Reed and Reed (1948). Five replicates of 0.01 ml from dilutions of cultures (10⁻⁵, 10⁻⁶, 10⁻⁷, 10⁻⁸) were delivered with a 0.1 ml Mohr pipet onto the surface of TSA plates. Plates were allowed to dry and were incubated in an inverted position at 27°C for 20-24 hours. Bacterial counts were made using a Bausch and Lomb dissection microscope, and replicates were averaged.

For each experiment, specific details of numbers, replicates and variations in technique are presented in the results together with the data deriving from that experiment.

Results

As will be noted from Table 1, chitinase production is a characteristic widely distributed among the varieties of *B. thuringiensis* tested. Indeed few varieties were without a chitinolytic strain, and their absence in varieties of *B.t. sotto* and *subtoxius* may simply reflect the minimal number of strains available for testing. Although the chitinolytic propensity seemed to cluster within specific crystal or serovar types (e.g. *kurstaki*, *entomocidus* or *darmsstadiensis*) it was not by itself a predictor of lethal potential.

On the other hand, there was a clear correlation between chitinase titre and lethality (Figs. 1,2). In Fig. 1 are shown results obtained when 8 cultivars of the *kurstaki* variety (H3a3b) were tested for effectiveness against spruce budworm. Mortality corresponded very clearly with concentration of chitinase generated. In Fig. 2 are shown results achieved with repeated trials of the cultivar HD-110 (*B.t.* var. *entomocidus*) harvested at different periods under the same conditions and yielding different amounts of chitinase. In this case too, there is an unequivocal relationship between the amount of chitinase present and mortality.

Table 1. The production of chitinase by selected taxonomic serovars of *Bacillus thuringiensis*¹

Varietal epithet	Serovar	Degree of Plate Clearing				Totals
		++	+	+/-	0	
<i>kurstaki</i>	H3a,3b	5	44	8	14	71
<i>thuringiensis</i>	H1	3	25	4	39	71
<i>initimus</i>	H2	4	0	1	3	8
<i>lesti</i>	H3a	1	16	3	4	24
<i>senyae</i>	H4a,4c	0	5	4	8	17
<i>israeli</i>	H4a,4b	0	0	0	1	1
<i>entomocidus</i>	H4a,4b	6	1	2	1	10
<i>allertiae</i>	H5a,5b	1	43	12	19	65
<i>entomocidus</i>	H6	2	0	0	3	5
<i>subtorosus</i>	H6	0	0	0	2	2
<i>izawa</i>	H7	1	37	6	2	47
<i>torosus</i>	H8a,8b	0	5	3	6	14
<i>colworthi</i>	H9	1	4	0	1	6
<i>canadensis</i>	H5a,5c	1	2	0	1	4
<i>armstrongii</i>	H10	6	4	0	3	13
<i>oumanoffii</i>	H11a,11b	0	1	1	0	2
<i>israeliensis</i>	H14	1	5	0	3	9
<i>ther</i>	-	2	2	1	2	7
unidentified	-	3	8	0	6	17

The degree of chitin-agar plate clearing was defined as follows: 0, no clear-zone visible in the agar surrounding colonies; +/-, a thin cleared ring around colonies just visible to the naked eye; +, a cleared ring around colonies about 1 mm wide; and ++, a cleared ring of 2 mm or more visible around the colonies on plate.

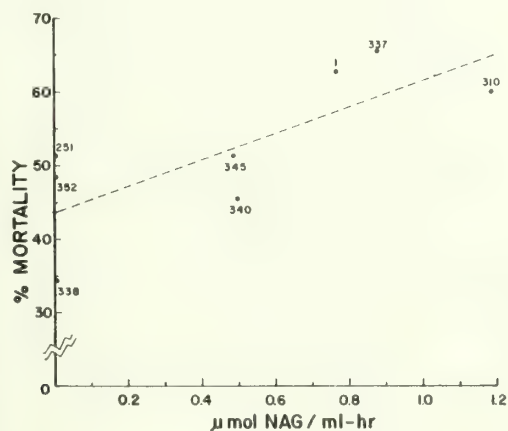


Fig. 1. Spruce Budworm mortality produced by 8 strains of *B.t.* var. *kurstaki* of varying chitinase titre. The strains were selected from one variety (serovar and crystal types, H3a,b and k-1, respectively) to minimize the effects of variables other than chitinase titre. All cultures were grown for 16 days in chitin broth medium. The initial number of larvae tested for each group was 35. Control mortality (not shown) was 5.7%. The correlation coefficient obtained for these points was $r = 0.75$; with 6 df, this gave 95% confidence limits by t-test. The number by each point is its HD number: HD-1 is the standard commercial strain.

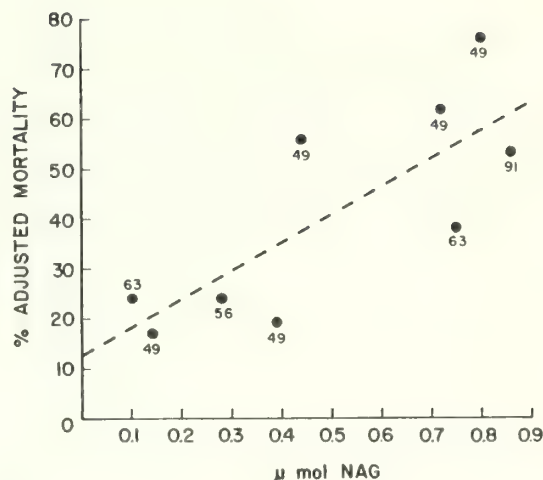


Fig. 2. The relationship of chitinase production in cultures of *B.t.* HD-110 (var. *entomocidus*) to mortality in spruce budworm.

The data points were calculated by means of Abbott's formula (1925) on mortality figures in each experiment to yield the "adjusted mortality" shown. The number by each data point gives the n for each experiment, the initial number of larvae in each treatment (and control) group. For these data, $r = 0.785$, significant at the 97% level of confidence by t-test with $df = 7$.

If one compares the overall efficacy of chitinase producing cultivars to that of the HD-1 strain currently in commercial use, the significant trend which emerges is the greater immediacy of kill achieved even though after 5 days the ultimate kill may be equivalent. It is clear (Fig. 3) that the presence of chitinase accelerates the general lethal action of *B.t.*

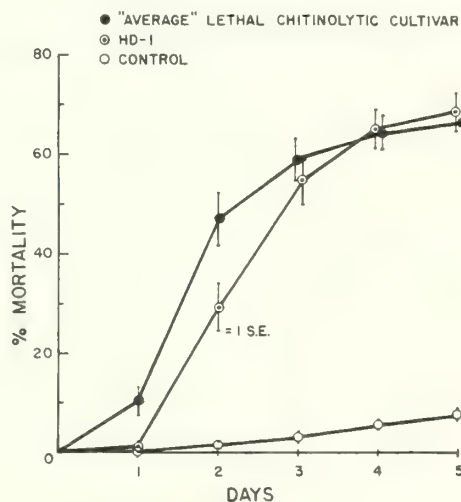


Fig. 3. Rate of kill of chitin grown *B.t.* strains compared with that of the commercial strain HD-1.

A composite of 9 separate experiments. The chitinolytic cultivars tested were HD's 7, 37, 48, 124a, 234, 287, 319, 340 and 539. Initial numbers per treatment group in each experiment ranged from 49 to 119, but each experiment was weighted equally to produce the average points

shown in the graph. The points for HD-1 and the controls are obtained from the same 9 experiments, and had the same initial n per group as their respective chitinolytic treatment groups.

The "chitinolytic cultivars" group results tested against that of HD-1 by ANOVA proved significantly different at the 0.05 level ($F = 4.92$, $df_1/df_2 = 1/80$). As the HD-1 actually produced higher ultimate mortality on day 5, this difference is plainly due to the distinctly higher mortality which the chitinolytic cultivars produced at the onset of the treatment exposure period.

That these effects are conditioned by the induction of chitinase is confirmed by the data in Table 2 and Fig. 4. The mortality achieved by cultivars grown in sporulation medium, i.e. in the absence of chitinase, is consistently and significantly lower than that achieved by the same cultures grown in a chitin medium for the induction of chitinase. As might be anticipated this, of course, did not hold true where the culture lacked the potential for inducible chitinases in significant amounts, the threshold level of available chitinase appearing at or above $0.6 \mu\text{mol}$ of NAG per ml-hour (see Table 2).

Table 2. A comparison of *B.t.* the lethality to spruce budworm of *B.t.* cultures grown in sporulation and chitin broth media, respectively.

Varietal	% mortality on 5th day		Chitinase titre
	Sporulation medium	Chitin medium	
HD-1	80.0	43.0	0.53 ¹
HD-37	28.5	51.8	0.93
HD-48	44.8	44.8	2.04 ²
HD-110	32.6	36.7	1.15 ²
HD-124a	20.6	23.8	1.5
HD-198	63.2	36.7	0.33 ²
HD-198	45.6	47.3	0.4 ³
HD-224	21.4	42.8	0.68
HD-226	37.4	58.7	0.96 ³
HD-232	40.2	42.8	5.5 ⁴
HD-234	46.4	66.0	1.27
HD-287	41.0	71.4	1.4
HD-323	58.4	61.4	0.75 ³
HD-498	44.1	62.7	1.62 ³
HD-500	22.0	19.0	0.1
HD-539	51.7	46.4	0.6 ⁵

¹ = μmol NAG/hr./ml. Usually HD-1 grown in chitin medium killed over 60% by day 5 (see Fig 1).

² = in this experiment, control mortality = 22.8% on day 5 (over 2x normal).

³ = sporulation culture tested alone. Chitin results are mean data from other experiments.

⁴ = reading on chitinase probably aberrant.

⁵ = in 4 other experiments, chitin cultures of HD-539 averaged 71.9% mortality and averaged over 1 in chitinase titre.

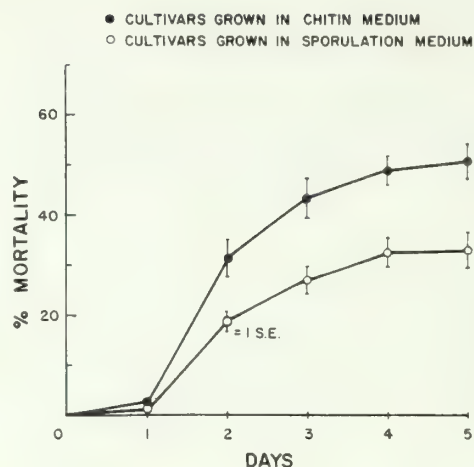


Fig. 4. Differential mortality to SBW achieved by cultures grown in chitin medium and sporulation medium.

This graph is a composite drawn from the data in Table 2. Cultivars HD-1, 198 and 500 have been omitted because of their low chitinase production, below $0.6 \mu\text{mol}$ NAG. The differences seen in HD-1 on Table 2 are extreme: see figs 1 and 3 for more usual values.

A further confirmation of the potential of chitinase active strains is shown in Fig. 5. In this instance, *B.t.* var. *galleriae* HD-287 (crystal type k-1) is consistently more lethal when induced for chitinase than commercial strain HD-1 or when grown in conventional sporulation medium. Again, as shown in Fig. 4, the significance of these results lies not only in the ultimate percentage kill achieved, but in the more rapid inception of kill and the minimizing of foliar damage this implies.

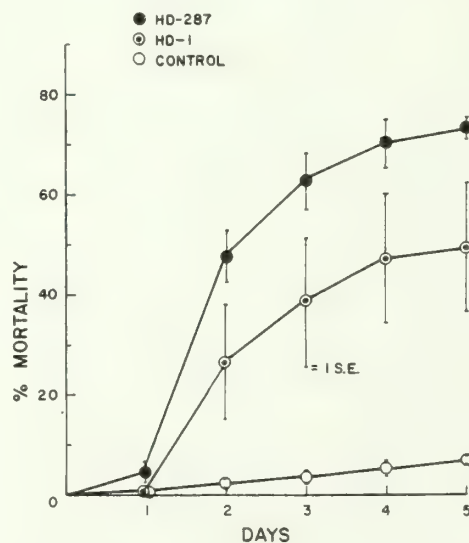


Fig. 5. Mortality to spruce budworm induced by *B.t.* HD-287, var. *galleriae* (crystal type k-1), and strain HD-1.

Composite data for 9 experiments. Although n, the initial number of larvae in each experiment

treatment group, varied from experiment to experiment (range = 42 to 70) data from separate experiments were averaged equally; it was felt that variation in mortality was due to larval batch tested and not random independent factors.

Data for HD-1 was drawn from only 4 experiments. In other cases, final mortality fell below 20% and was discarded as unrepresentative (see Fig. 3 for other HD-1 data).

This extreme variability in HD-1 lethality, as reflected in the S.E. shown here, is a common problem with this strain (N. Dubois, pers. comm.).

For 3 experiments (run as part of those above) *B.t.* HD-287 was tested as grown in sporulation medium. On day 5, mortality was $\bar{x} = 50.6\% \pm 6.84$ (= S.E.).

Discussion

In contrast to the findings of Smirnov and Valero (1977), the capacity for chitinase production would appear to be widespread and not confined to a varietal type. Within each varietal type there is, to be sure, a wide range of chitinolytic activity. For the *kurstaki* variety on which we report, the degree of enhanced lethality appears directly related to the titre of active chitinase. Certainly these results invite investigation of the relationship between chitinase and lethality within other varietal groups.

Although the phenomenon of chitinase enhanced lethality by *B.t.* to SBW seems unequivocal from the foregoing, further work is clearly required to elucidate the precise, operative mechanism. On the basis of the work reported by Dubois (1977), one may infer that there is an erosion of the peritrophic membrane. This facilitates entrance of spores as well as adventitious microflora into the larval haemocoel resulting in a broader and more diffuse disruption of various physiological and metabolic processes. Death occurs more rapidly in a population rendered more susceptible by these plural effects. A number of issues, however, remain speculative at this time. There is a discomfiting variability in the chitinase yield generated from the same culture grown under presumably identical conditions. This might suggest the presence of a catabolite repressor analogous to the cellulase system and a feedback mechanism that may inhibit the sustained production of chitinase. Additionally, it should be mentioned that the production of chitinase and the dissolution of the parasporal crystal and subsequent release of the toxic fraction represent antithetic pH demands: the pH optimum for chitinase lies at 5.5 to 5.8; for crystal dissolution above about 8. It is therefore remarkable that sites are present in the insect gut where both these agents may express themselves. However, there does appear to be a marked potential for chitinase activity at the peritrophic membrane of the Douglas fir tussock moth, *Orgyia pseudotsugata*. Studies by Brandt *et al* (1978) report that both chitinase and protease degraded the peritrophic membrane, releasing products of hydrolysis and effecting structural changes in the membrane. Although work in our

laboratory showed that many strains of *B.t.* such as HD-287 do produce proteases, no clear-cut relationship between protease titres and mortality could be demonstrated.

A final question around which there has been much speculation has been our sustained inability to achieve any consistent enhancement of *B.t.* virulence with commercial chitinase. It might have been presumed that the lytic effect generated by this enzyme could have provided an additive measure of lethality in the same way provided by the chitinase induced in the chitinase active *B.t.* strains. Two explanations offer themselves for this failure: 1. the chitinase must be of a specific character capable of catalyzing the depolymerization of the chitin in the SBW gut; or 2. that the enzyme is operative only when membrane bound and responds to the presence of an additional factor provided by this linkage. The role of vegetative cells, always present in small numbers in treatment aliquots is also unclear. Though the event of increased lethality as a consequence of the presence of microbial chitinase seems certain enough, the precise details of its nature await further clarification.

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THE BIOCHEMISTRY OF THE PROTEIN CRYSTAL TOXIN OF *BACILLUS THURINGIENSIS*

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The crystal consists of dimeric protein subunits. The monomer peptide chains are held together in the subunit and the subunit in the crystal by disulfide and non-covalent bonds. The monomer peptide has a molecular weight of about 130 kdaltons which, in the presence of proteases, is hydrolyzed to a protease-resistant-protein of 65 kda that is toxic both to larvae by injection and to tissue culture cells and thus is the active toxin. The gene for this protein is on a plasmid which greatly simplifies the work of the genetic engineers. The gene has been partially sequenced and the secondary structure of this part has been predicted but not demonstrated.

Bacillus thuringiensis (Bt) is divisible into 20 varieties or serovars based on serological and biochemical tests on the vegetative cell. The protein that is responsible for most of the toxicity, and especially for the insecticidal activity of commercial preparations, is produced as a bipyramidal crystal during sporulation of the *Bacillus* (Fig. 1). The surface pattern observed

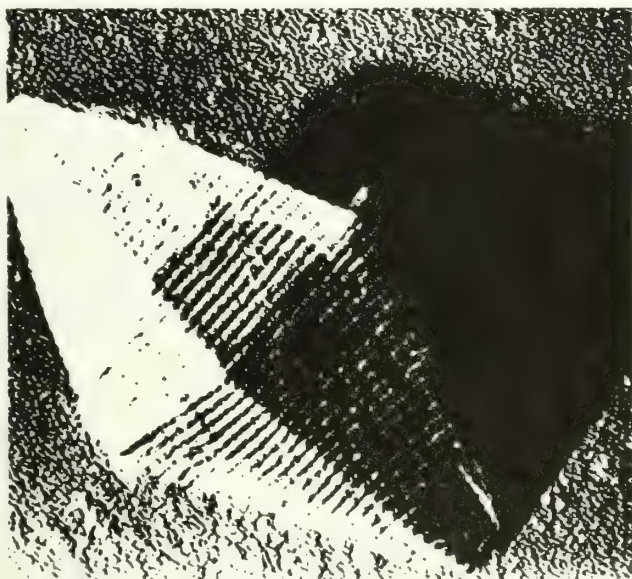


Figure 1. Electron micrograph of a parasporal crystal of *Bacillus thuringiensis* (Courtesy of C. Hannay)

is due to the regular positioning of rod-shaped molecules with dimensions of about 9 X 13 nm and a calculated molecular weight of 230,000 daltons (1 dalton is the mass of a hydrogen atom) (Holmes and Monroe, 1965). The shapes of the crystals vary from almost cuboidal to slender needle shapes depending on the serovar. Isolates can often be recognized by crystal shape alone.

Serology of the crystal broadly reflects the groupings referred to above but with considerable overlap (Krywienczyk et al., 1978, 1981). In this review I shall refer to serovars by their full names but crystal types by their first 3 letters, or in the case of *kurstaki* crystal types to K-1' and K-73, as suggested by Krywienczyk et al. (1978).

Many of the problems of dissolving and characterizing the crystal that have historically plagued the study of Bt crystal toxin have been overcome in the past 5-8 years. Crystals are now readily separated from spores (Milne et al., 1977, Sharpe et al., 1975) and can be freed of the proteases that are adsorbed to the crystal which have, in the past, caused confusion about the molecular weight of the constituent peptide chains (Chestukhina et al., 1978; Nickerson and Swanson, 1981).

The techniques for dissolution of the crystal are also now reasonably defined. The crystal is held together principally by intermolecular disulfide bonds of which there are as many per peptide chain as in wool keratin (Huber, 1982) and by noncovalent interactions such as salt bridges and hydrogen bonds. Highly alkaline conditions (pH 11-13) dissolve the crystal by alkaline hydrolysis of disulfide bonds but a considerable loss of toxicity proportional to the length of time in alkali occurs (Trumpi, 1976). Under less alkaline conditions (pH 9.5-11) dissolution will occur in the presence of disulfide reducing agents such as dithiothreitol (Dtt) or mercaptoethanol and toxicity is preserved. Under near neutral pH conditions denaturants such as ionic detergents, guanidine hydrochloride, urea, or chaotropic salts are required along with disulfide reducing agents and in most cases toxicity is totally destroyed. Huber (1982), however, describes conditions for the dissolution of crystals in guanidine hydrochloride in which toxicity is retained. The toxicity is also destroyed by heat as well as by denaturants, leading to the conclusion that secondary structure (helical or beta organization) or tertiary structure (packing of the helical or beta structural elements) of the crystal protein is required.

A protein with a molecular weight of about 230 kilodaltons (Kda) is obtained when the crystal is dissolved under carefully controlled conditions without reducing agents (Huber 1982). This is in good agreement with the molecular

weight calculated from the x-ray data (see above). In the presence of reducing agents a single molecule with a molecular weight of 130 kda is observed indicating that the unreduced molecule is probably a dimer. Although this has generally been the accepted interpretation, Huber (1982) was the first to present data clearly supporting this interpretation. The discrepancy in the molecular weights observed in the monomer and the dimer remains unresolved where molecular weights are determined by electrophoresis in SDS. Ultracentrifugation (Huber, 1982; Glatron et al., 1972) gave lower values for the monomer but the dimer molecular weight is exactly 2X that of the monomer. For the sake of clarity let us accept the 130 kda molecular weight in the balance of this discussion.

The amino acid compositions vary from serovar to serovar (Table I). The greatest variability is seen in the charged amino acids and glycine. The dicarboxylic amino acids aspartate and glutamate are present in unusually high amounts in all serovars, about half as their amides glutamine and asparagine (Glatron et al., 1972; Fast, 1981).

Table I. Amino acid compositions and minimal molecular weights

AA/type	<i>thu</i> (8) ^a	<i>fin</i> (2) ^b	<i>sot</i> (3) ^c	<i>ale</i> (3) ^d
Asp	14	14	13	14
Thr	8	8	7	8
Ser	8	9	8	9
Glu	13	12	15	14
Pro	5	6	8	6
Gly	10	15	9	12
Ala	8	13	7	8
Val	8	9	6	9
Cys	1	2	1	2
Met	1	1	1	1
Ile	7	8	8	8
Leu	11	11	13	11
Tyr	5	4	5	5
Phe	5	4	6	5
Lys	4	6	4	4
His	2	3	2	2
Arg	6	3	8	7
Try	1	1	1	1
min. mol. wt.	12820	13231	13231	11895

<i>tol</i> (2) ^e	<i>gal</i> (2) ^f	<i>ken</i> (2) ^g	<i>and</i> (1) ^h	<i>kur-1</i> (1) ⁱ
15	16	15	12	14
9	9	8	7	7
12	11	9	8	9
12	13	14	15	13
6	7	5	7	4
16	11	9	10	8
11	10	8	8	6
8	8	8	7	8
1	2	2	2	2
1	1	1	1	1
8	8	8	7	6
10	13	13	11	9
3	5	5	4	5
4	5	6	5	4
3	4	5	4	3
2	3	2	3	2
5	7	7	6	9
ND	1	ND	1	1
12796	14291	13042	13282	12400

Considerable controversy exists as to whether carbohydrate is bound to the crystal protein and is essential to toxicity. Several workers have reported concentrations of carbohydrate in the crystal ranging from 0.5% to 12% in crystals (Holmes and Monroe, 1965; Bateson and Stainsby, 1970; Bulla et al., 1977). Other investigators working with related isolates failed to detect carbohydrate in rigorously purified crystals (Lecadet, 1965; Huber et al., 1981). Treatment with carbohydrases to remove sugars or with immobilized concanavalin A to remove glycoproteins containing glucose and mannose (the sugars reported to be present) from solution failed to materially reduce toxicity (Fast, 1981). Amino sugars or sialic acids, often associated with glycoproteins, were not detected in the crystal (Fast, 1981; Bulla et al., 1977; Bateson and Stainsby, 1970). Whether the carbohydrates are covalently bound to the peptide chain or only adsorbed to it, they do not appear to participate in toxicity to insects. There is no lipid or nucleic acid associated with the crystal.

The monomeric 130 kda peptide chain is a protoxin that must be activated by proteolytic hydrolysis (Lecadet and Martouret, 1965; and many others). The activated product is generally a protease resistant protein (PRP) with a molecular weight in the range of 50-70 kda although smaller toxic fragments have frequently been reported but generally not well documented (Fast and Angus, 1970; Pendleton, 1973; Faust et al., 1974). Lecadet and Dedonder, (1967) isolated and partially characterized 2 small toxic peptides from 350mg of starting proteolytic digest. Work on this scale has not been repeated.

The amino acid composition of PRP is significantly different from that of the crystal. Amino acid compositions of PRP from 3 serovars are shown in Table II (Chestukhina et al., 1982). A major reduction in the amount of lysine and an increase in hydrophobicity in PRP over that of the protoxin is observed. In the light of Bee-ple's finding (Abstract, Ithaca meeting of the SIP, 1983) that the toxicity spectra of activated PRPs is the same as the spectra of the crystal, the differences in amino acid composition seen in the table are probably significant.

There are significant sequence differences in PRP of these serovars as well. SDS gels of cyanogen bromide cleavage products of PRP from 3 different serovars have been published (Chestukhina et al., 1982) (Fig.2). Cyanogen bromide cleaves peptides only at methionine. Because the products of cleavage have different molecular weights in the three serovars shown, sequence differences must exist and again are likely to affect toxicity spectra.

Table II. Comparison of the amino acid composition of the PRP of 3 serovars of *Bacillus thuringiensis* (from Chestukhina 1982).

Amino Acid	<i>galleriae</i> 65 kda (mol%)	<i>tolworthi</i> 65 kda (mol%)	<i>alesti</i> 70 kda (mol%)
1/2 cys	1.0	1.0	1.0
asp	11.7	11.7	11.1
thr	6.6	8.0	6.3
ser	11.8	9.8	9.4
glu	11.2	10.5	11.0
pro	5.1	4.8	5.7
gly	7.6	7.5	8.0
ala	6.2	5.7	5.7
val	4.9	4.4	7.3
ile	5.5	6.8	6.3
leu	8.5	9.3	9.8
tyr	3.6	3.9	3.1
phe	4.2	5.5	6.0
his	1.7	1.4	2.1
lys	1.3	1.0	1.0
arg	6.2	6.9	5.0
met	0.7	1.0	0.7
trp	0.7	0.6	0.6

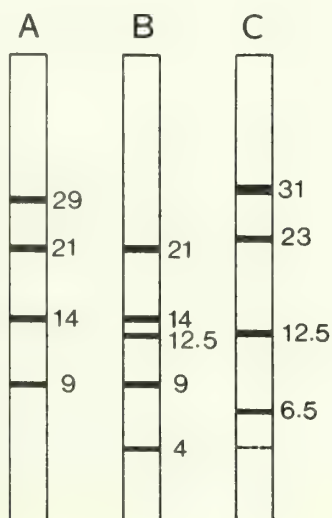


Figure 2. SDS-Page patterns of PRP of serovars (A) *tolworthi* (B) *alesti* and (C) *galleriae* after treatment with cyanogen bromide. Numbers are molecular weight in kda.

Recently the gene for the 130 kdalton peptide has been cloned and expressed in both *E. coli* and *Bacillus subtilis* (Schnepf and Whiteley, 1981; Klier et al., 1982). The expressed protein in both these hosts has been shown to be toxic to lepidoptera. The sequence of the first 333 residues of this protein from HD-1 Dipel have been inferred from the nucleotide sequence of the gene (Wong et al., 1983). In fig. 3 I have reproduced that sequence and have marked the hydrophobic and charged amino acids.

```

      10      20      30      40      50      60
- - - - - + - - - - -
MDNNPNINECIPYNCLSNPEVEVLGGERIETGYTPIDISLSLTQFLSEFVPGAGFVLGL
* * * * *

      70      80      90      100     110     120
- - - - - + - - - - -
VDIIWGIFGPSQWDAPVQIEQLNQRIEFARNQAISRLEGLSNLYQIYAESFREWEAD
* * * * *

     130     140     150     160     170     180
+ + - - - + - - - - -
PTNPALREMERIQFNDMNSALTITPLLAVQNYQVPLLSVYVQAANLHLSVLRDVSFVQC
* * * * *

     190     200     210     220     230     240
+ - - - - + - - - - + - - - - + - - - -
RWGFDAATINSRYNDLTRLIGNYTDYAVRWYNTGLERVWGPDSRDWVRYNQFRRLTLTV
* * * * *

     250     260     270     280     290     300
- - + - - + - - - - - + - - - - + - - - -
LDIVLFSNYDSRRYPITVSQLTRELYTNPVLENFDGSPFRGMAQRIEQNIQPHLMIDL
* * * * *

     310     320     330
- - + - - + - - - - -
NSITIIYTDVHRGFNYWSHQITASPVGFGSGPEF
* * * * *

```

Figure 3. Amino acid sequence of the N-terminal 333 amino acids of the HD-1 Dipel crystal protein. Amino acids are designated by the single letter code. * designates hydrophobic amino acids. Charged amino acids are designated by + or -.

Techniques are available for predicting the secondary structure of a protein from sequence information (Chou and Fasman, 1978). I have applied these techniques to the crystal protein sequence and show the probable position of turns and of alpha helical and beta structures (Fig.4).

Because many of the turns are so tight, only 4-8 residues, it is likely that at least some of the beta structure is antiparallel. While such predictions of structure are of limited accuracy there are good indications that turns and secondary structure are highly conserved, even more highly than sequence, in homologous proteins. The availability of additional sequences, which are presently being derived, should greatly assist in identifying the structure(s) responsible for toxicity.

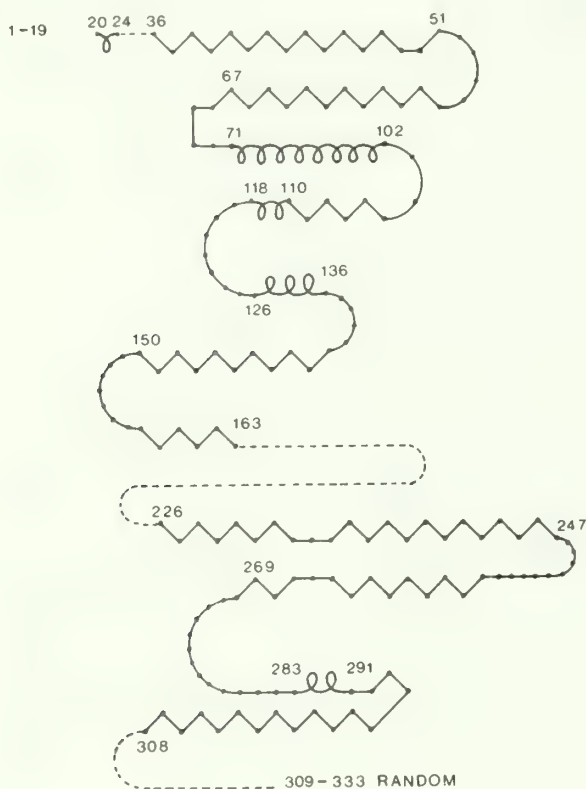


Figure 4. Secondary structure of the N-terminal 333 residues of HD-1 dipel crystal protein as predicted by the method of Chou and Fasman (1978). Zigzag indicates beta structure, coils indicate helices, and dashed lines indicate random structures. Chain reversal indicates predicted turns.

Utilizing a program developed to detect repetition of sequences, I have found no repeating sequences in these first 333 residues. This and the observation that the gene product has a molecular weight of 130 kda indicates that the subunit cannot be composed of aggregates of small peptides as previously suggested (Fast and Martin, 1980).

So what? The subtitle of this session is "Where do we go from here?" What I have reviewed in this paper is the barest of beginnings, but it is a beginning. We do not know what the structure of PRP is, nor even where it comes from in the sequence of the monomer. We do not know what the active structures are in PRP. We do not know how different isolates within a serotype with different toxicity spectra differ from each other, much less how toxins from different serotypes differ. We do not know why the toxicity of a single isolate varies so much between target insects; it may be because of differences in their proteases or their toxin receptors if there are such (I think there are!). In some cases we have hints, but nothing solid. When we know the answers to these questions then I predict that molecular biologists will be able to tailor make a crystal protein for each pest or crop, and Bt or related products could dominate the insecticide market for defoliating insects. The potential is enormous.

If Bt is to reach this potential it will be necessary to recruit and support much more fundamental work on crystal toxin. Because of its economic interest, its potential for much more benign pest control, and its potential for genetic manipulation interest is growing but support is meager. We need to convince our colleagues doing fundamental work on protein structure and molecular genetics that Bt is a good model for study. More particularly we need to convince the funding agencies of the value of such work so that it is supported. Significant growth in support of such fundamental studies is required to realize the potential of this organism for environmentally benign insect control.

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SELECTION OF ACTIVE STRAINS OF THE GYPSY MOTH NUCLEARPOLYHEDROSIS VIRUS

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The gypsy moth Lymantria dispar (linnaeus) has grown in economic importance as an insect pest over the past 75 years. From a localized infestation of a small geographical area of New England, the gypsy moth has spread to such an extent that is now found over much of the United States. Control measures are varied, but effective biological control is needed to control pest populations, especially in such sensitive areas as parks, residential areas, and municipal watersheds.

A nuclear polyhedrosis virus (NPV) of the gypsy moth has been registered for control purposes; however, efficacy is variable and borderline in control situations. Natural epizootics of the virus are extremely effective in destroying natural populations. The disparity in efficacy between natural virus outbreaks and artificial application of laboratory produced gypsy moth virus presents an obvious research problem for the selection of a more 'potent' strain of the virus. The approaches that we have taken involve: (1) in vitro strain selection; (2) evaluation of naturally occurring geographical isolates; (3) in vivo passage through L. dispar; and (4) in vitro and in vivo mutagenesis.

In vitro strain selection

Cell lines of ovarian origin were obtained by Dr. R. H. Goodwin of the Insect Pathology Laboratory (BARC-USDA). Using the IPLB-652Y cell line, a plaque assay was developed (Fig. 1), which not only allows for quantification of non-occluded virus but also allows for studying the replication and genetics of LdMNPV. Using the plaque assay, 13 plaque isolates were made and their virulence compared to the LDP-67 strain (U.S. Forest Service, Hamden, CT) (Table 1). No one isolate was more virulent than the standard (LDP-67); however, a few isolates (5-7D, 14-4C) were close in activity. There was a wide range in activity with three samples giving no activity greater than 4250 times an LD₅₀ for the LDP-67 isolate.

Isolation of DNA from the plaque isolates listed in Table 1 and digestion with restriction endonucleases (REN) showed that the twelve isolates could be separated into a least five groups based upon the profile of REN digests. Differences in the digestion profiles can be observed in Figure 2, which shows an EcoRI digest

of the plaque isolates. Although many bands are common to the plaque isolates, obvious differences do exist. A summation of differences found among the twelve isolates using the restriction enzymes SAL I, BGL II, BAM HI, HlnD III, and EcoRI are presented in Table 2. Utilization of the five enzymes tests produced five different groupings of isolates with common REN patterns. Use of additional restriction enzymes could potentially show further dissimilarities.

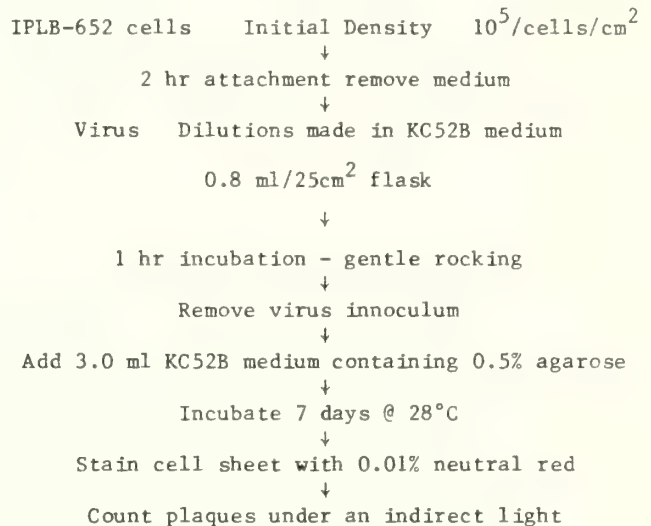


Figure 1.--A plaque assay for Lymantria dispar MNPV using the IPLB-652 cell line.

Thus, comparison of the five groupings of plaque isolates having common patterns (Table 2) and virulence (Table 1) show that genotypic variants of L. dispar NPV do display differential virulence. These studies have shown that there is a diversity of genomic material within isolate LDP-67.

Naturally-occurring geographical NPV isolates

Differences in biological activity can be detected among geographical isolates of the same NPV species (Ossowski 1960, Smirnov 1961, Chauthani et al. 1968, Shapiro and Ignoffo 1970), including the gypsy moth NPV (Magnoler 1970, Rollinson and Lewis 1973, Vasiljevic and Injac 1973). Our objective was to identify the most active isolates by comparing NPV isolates from North America, Europe, and Asia (Shapiro et al. 1984). Eighteen isolates of L. dispar NPV were harvested from both laboratory and field-collected larvae, and were compared to a Connecticut standard (LDP-67) is standardized bio-assays (Shapiro and Bell 1981). LD₅₀s varied from 1.7×10^3 polyhedral inclusion bodies (PIB)/ml ($=0.34 \times 10^0$ PIB/mm² of diet surface) to 5000×10^3 PIB/ml ($=1 \times 10^3$ PIB/mm²), a difference of about 2940-fold (Table 3). The most active NPV isolates generally originated from North America, the least active isolate originated from Asia (Japan). In the highest activity group, one

Table I. Bioassay of L. dispar Multiple Embedded Nuclear Polyhedrosis Virus
Plaque Isolates

Plaque Isolate	LD ₅₀ (PIB/ml X 10 ⁴)	Relative Efficiency (Percent)	Plaque Isolate	LD ₅₀ (PIB/ml X 10 ⁴)	Relative Efficiency (Percent)
LDP-67	1.77	100.0			
5-7D	5.83	30.3	9-12	66.00	2.6
14-4c	6.57	26.9	7-109	125.35	1.4
12-4b	7.97	22.2	6-9a	7500	.02
11-13c	8.60	20.5	14-10b	7500	.02
13-7a	9.00	19.7	15-10c	7500	.02
10-13a	10.47	16.9			
16-13a	14.33	12.3			
8-12	15.00	11.8			

Figure 2

ECO RI DIGEST OF PLAQUE PURIFIED ISOLATES
OF THE LDP-67 STRAIN OF MLd NPV

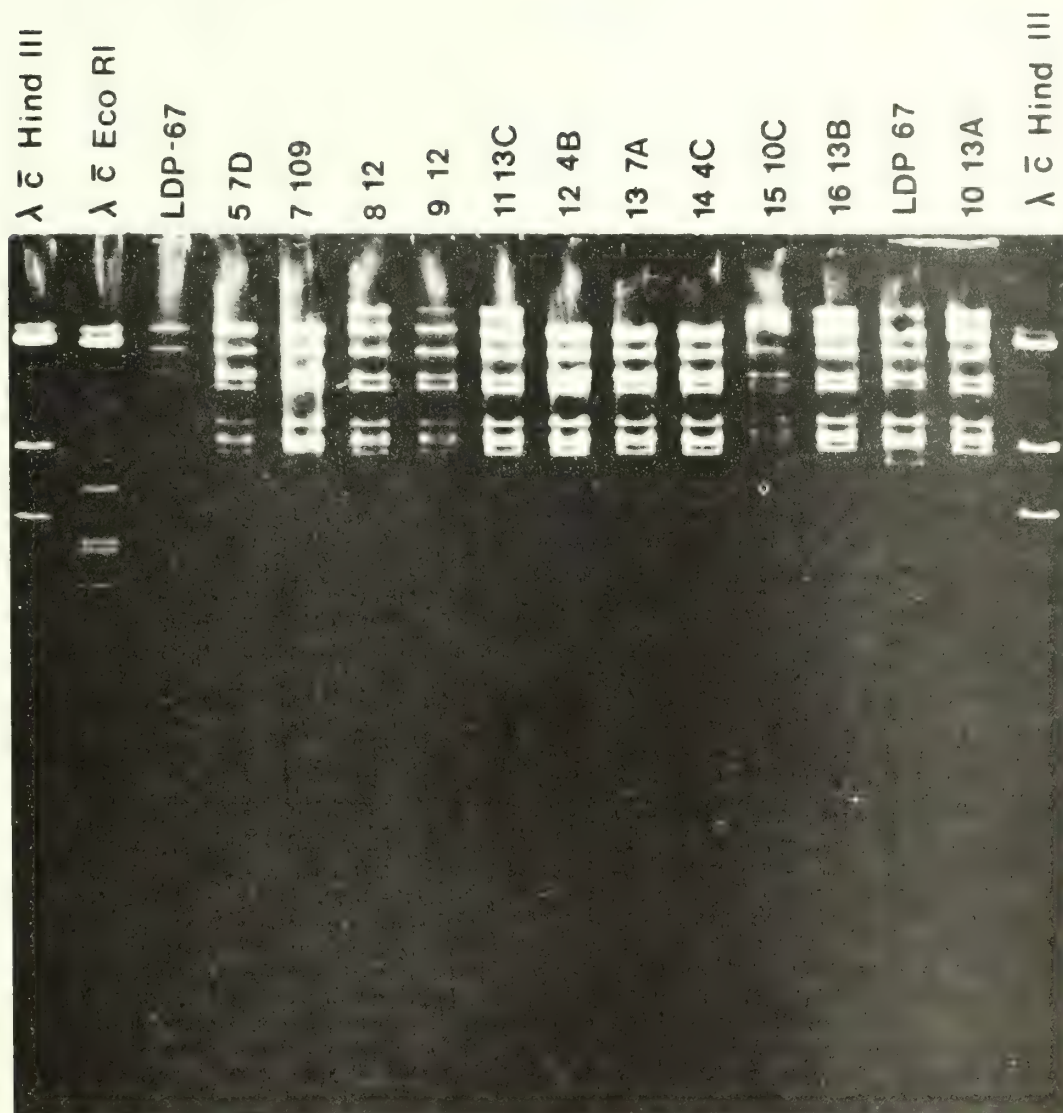


Table 2. LdMNPV Plaque Isolates: Summary of Grouping of Isolates According to REN Profiles

		Sal I	Bgl II	Bam HI	Hind III	Eco RI
LDP-67	(WT)	X	Y	Z	A	A
1D	5-7d	X	Y	Z	B	A
1F	7-109	X	Y	Z	A	A
1g	8-12	X	Y	Z	A	B
1h	9-12	X	Y	Z	-	B
1j	11-13c	X	Y	Z	A	B
1k	12-4b	X	Y	Z	B	A
1l	13-7a	X	Y	Z	B	A
1N	14-4c	X	Y	Z	B	A
1o	15-10c	X	Y	Z	-	B
1p	16-13b	X	Y	Z	A	B
1q	6-9a	X	Y	Z	A	C
1i	10-13a	X	Y	Z	C	B
Plaque Isolates with Common REN Patterns						
aa	ab	ba	ac	cb		
LDP-67	1g	1d	1q	2i		
1f	1j	1k				
	1p	1l				
		1n				

Table 3.--Comparatige biological activities of
L. dispar NPV isolates

NPV ISOLATE TESTED	LC ₅₀ (95% CL) PIB/ml x 10 ³
QUEBEC 1	1.7(1.1-2.6)
ABINGTON, MASS.	1.8(1.0-3.3)
QUEBEC 2	2.4(0.8-6.4)
DIGHTON, MASS.	3.0(2.4-5.8)
BALD EAGLE, PA.	3.7(2.9-4.7)
LDP-67(CT STD)	4.8(4.0-5.8)
HOUGHTON POND, MASS.	5.0(3.3-7.6)
NEW HAMPSHIRE	6.8(5.3-8.8)
MIDDLEPORT, PA.	8.0(6.3-10.6)
ROMANIA	13.1(10.6-16.2)
SANDWICH, MASS.	21.0(14.9-29.6)
BRIDGEWATER, MASS.	21.4(13.4-33.7)
ORANGE, MASS.	27.3(17.3-43.5)
SERBIA-YUGOSLAVIA	28.8(23.3-35.6)
USSR	31.3(26.6-36.9)
SLOVANIA-YUGOSLAVIA	57.1(22.3-133.8)
DALMATIA-YUGOSLAVIA	59.3(48.7-72.2)
SPAIN	78.8
JAPAN	Greater than 5000

(From Shapiro et al. 1984).

isolate came from the United States (Abington, MA), and two came from Canada (Quebec 1 and 2). In the next activity level, one isolate came from Dighton, MA and one came from Bald Eagle, PA. Since these five isolates were significantly more active than the CT standard, they might be potential candidates for use as microbial control agents. The European isolates were in the sixth to eleventh activity levels. At a concentration of 5000x10³ PIB/ml, the Japanese NPV caused only 16% larval mortality, whereas lower concentrations were not lethal (Shapiro et al. 1984).

Virus was purified from pooled cadavers from these experiments and the respective viral genomes were purified and digested with a variety of restriction enzymes. As in the previous instance, there is a variation in bands of restriction fragments among the various geographical isolates, showing a great heterogeneity both intra-strain and inter-strain among L. dispar NPVs. Using a nick translated probe of the genome of LDP-67 to hybridize against a Southern blot of Figure 3, it was found that the greatest homology between LDP-67 and foreign isolates occurred among North American

isolates, intermediate homology occurred with European isolates, and no homology occurred with the Asian isolate. Thus, reports stating the gypsy moth is an evolving species whose North American members now have different physiology, behavior, etc. could also pertain to the gypsy moth NPVs.

In vivo passage through Lymantria dispar

Eight virus isolates (USA-LDP-67; ROMANIA, SPAIN, USSR, YUGOSLAVIA-DALMATIA, SERBIA, SLOVENIA) were selected serial passage through second-stage L. dispar larvae. While the activity of the American isolate did not change during the four passages, activities of all other isolates increased significantly during the second passage (Table 4). Moreover, the activity of the Japanese isolate increased ca. 1000-fold during the passages. In general, activities became stabilized from the second to the fourth passage and were quite similar to that of LDP-67. The experiment was terminated after the fourth passage, since it was assumed, based upon the behavior of LDP-67, that further increase in activity would be minimal. While serial passage resulted in greater activity (see also Veber 1972, Shapiro and Ignoffo 1970), these isolates were still significantly less (P<.05) than the most active North American isolates (Quebec 1, Quebec 2, and Abington, MA) (Shapiro et al. 1984).

Since the NPV isolate from Abington, MA had greater biological activity (P<.05) than the LDP-67 standard, a concentrated effort was made to characterize this isolate, in terms of activity. The Abington isolate was serially passed, along with the LDP-67 isolate, at LD₅₀ values. As was seen previously, serial passage of LDP-67 did not result in any change in activity, which indicated the stability of the isolate. Surprisingly, the activity of AB decreased during early passage through second-stage L. dispa larvae, but the NPV was still more active than the LDP-67 standard (Fig. 4). During subsequent passage of AB, however, activity increased to the original value, and remained stable during the last three passages. A sample of AB was then forwarded to the U.S. Forest Service Laboratory, Hamden, CT for testing. The high activity of this isolate was confirmed (W. Rollinson, personal communication) and large amounts of this isolate will be produced for subsequent field-testing.

Mutagenesis

In addition to identifying and monitoring natural genetic variation, artificially induced genetic variation is also being investigated. Over ten years ago, Reichelderfer and Benton (1973) reported that four treatments of an NPV (Spodoptera frugiperda) with 3-methylcholanthrene resulted in a nine-fold increase in virulence. A significant decrease in the Lt₅₀ was observed during bioassays comparing treated and untreated virus. Moreover, similar results were observed with 1,2,3,4-dibenzanthracene, 5-bromodeoxyuridine,

Figure 3

GEOGRAPHICAL ISOLATES OF
LYMANTRIA DISPAR NUCLEAR POLYHEDROSIS VIRUS
DIGESTED WITH BAM HI

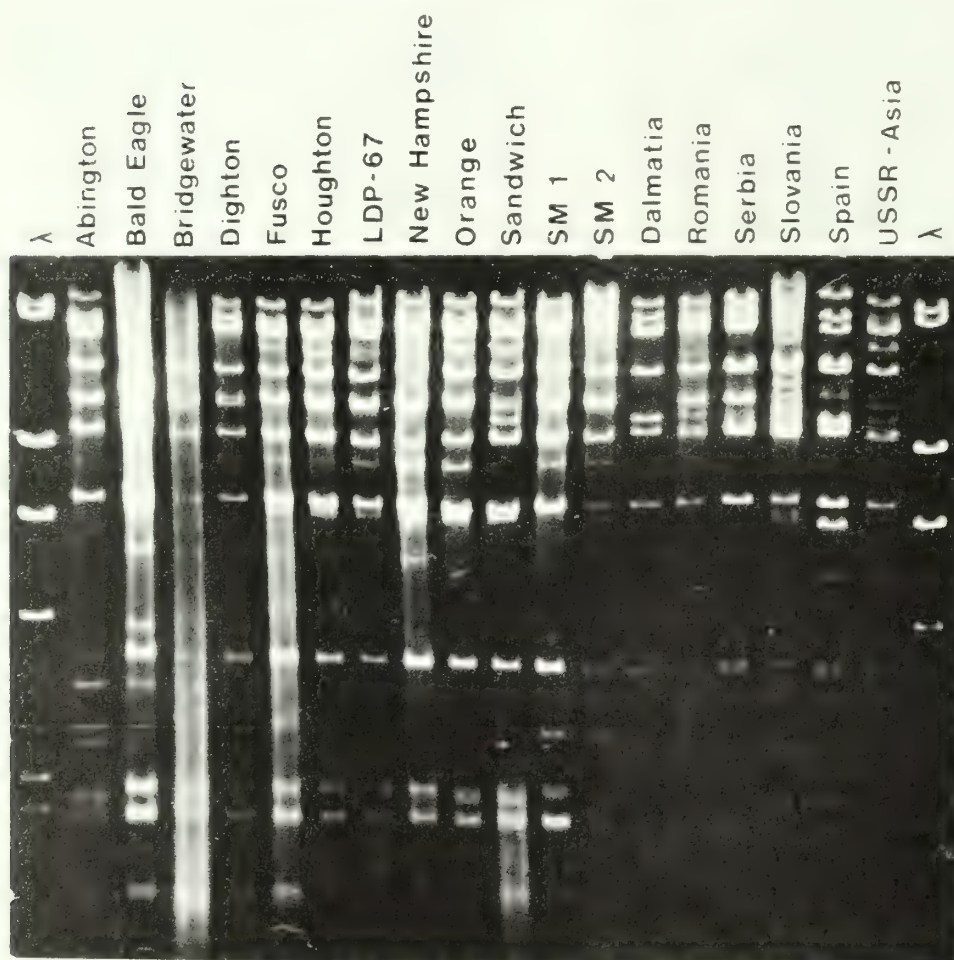


Table 4.-

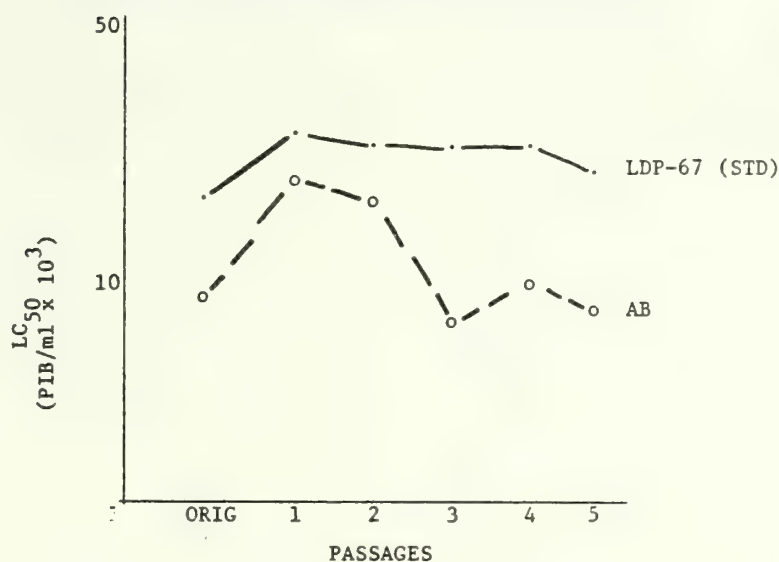
BIOLOGICAL ACTIVITIES OF NPV ISOLATES SERIALY PASSED
THROUGH L. dispar LARVAE

NPV ISOLATES TESTED	LC ₅₀ (95%CL)(PIB/ml x 10 ³) AT PASSAGE	
	1	4
LDP-67 (STD)	6.26(3.98-9.58)	6.06(4.61-7/97)
SPAIN	94.6(41.2-200)	5.60(3.36-9.16)
ROMANIA	14.1(9.05-21.7)	5.82(2.42-13.2)
DALMATIA-YUGO	59.6(29.6-117.2)	6.10(4.30-8.60)
SLOVANIA-YUGO	57.6(25.9-120)	8.00(6.09-10.5)
SERBIA-YUGO	33.6(17.3-63.2)	9.95(6.35-15.4)
USSR	29.8(18.8-44.8)	5.87(4.47-7.67)
JAPAN	5000+	9.53(5.98-15.4)

(From Shapiro et al. 1984).

Fig. 4

SERIAL PASSAGE OF ABINGTON, MA NPV ISOLATE



N.B. ORIGINAL AB NPV ISOLATE WAS ALSO BIOASSAYED AT EACH PASSAGE, AND THE LC₅₀ VALUES WERE 8.0, 8.3, 7.2, 9.6, AND 9.1 (MEAN VALUE = 8.44 x 10² PIB/ML).

and 5-iododeoxyuridine. In the case of the alfalfa looper (Autographa californica) NPV, however, no significant effects were noted with 5-bromodeoxyuridine or n-methyl-n'-nitro-n-nitrosoguanidine (McClintock 1980) in the cabbage looper, bollworm, tobacco budworm, or fall armyworm. A mutant of the alfalfa looper NPV (=HOB) was obtained in vitro after treatment with 2-aminopurine, which possessed increased virulence (Wood et al. 1981). In our investigations, in vitro experiments are now in progress using the mutagen 2-aminopurine. These experiments, along with co-infection studies with homologous and heterologous virions and genomes (co-transfection) to generate non-genetically engineered recombinant viruses should produce genomes having artificially or non-naturally occurring genetic variation. In addition, in vivo studies are now in progress using such mutagens as bromodeoxyuridine, bromodeoxycytidine, 2-sminopurine, ethyl methyl sulfonate, hydroxylamine, acriflavin, proflavin, and hydrogen peroxide, among others. More virulent strains are hoped for from these studies.

The empirical search for an array of genes which will produce a more virulent strain of LdMNPV has been or is now undergoing all classical and standard methods used to produce virulent strains of virus both in animal virology and in insect virology. Failure to produce such a strain does not imply that these methods be abandoned; however, the use of new strategies developed from the Biology revolution of the last decade should be considered. If lessons are to be learned from other viruses which have been manipulated by these methods, then a large amount of fundamental work such as described is necessary to intelligently modify current Lymantria dispa nuclear polyhedrosis viruses.

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PATHWAYS OF NUCLEOPOLYHEDROSIS VIRUS INFECTION IN
THE GYPSY MOTH, LYMANTRIA DISPAR¹

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Gypsy moth nucleopolyhedrosis virus polyhedral inclusion bodies dissolve slowly in host digestive fluids, *in vitro*. Infectious viral material is in the hemocoel two hours after ingestion of inclusion bodies. Hemocytes produce and release nucleocapsids throughout the course of infection, but in the fat body, nearly all nucleocapsids are enveloped and occluded.

Although the virus disease of the gypsy moth was reported as early as 1911 (Reiff 1911), very little attention has been given to the mode of action of the causative agent. This report deals with some of the steps in the pathway of nucleopolyhedrosis virus (NPV) invasion and infection in the gypsy moth.

First of all, we know that gypsy moth larvae can become virus-infected by ingesting polyhedral inclusion bodies (PIBs), but we don't know a great deal about what happens to PIBs once they've been ingested. A recent study of PIB dissolution in gypsy moth digestive fluid indicates that the dissolution process may be rather slow; significant dissolution occurred only after two hours incubation (Shields 1984a). We know that factors such as pH, ionic strength and enzymatic activity can be important in PIB degradation (Nordin and Maddox 1971, Paschke and Summers 1975, Wood 1980), and we know that some conditions, such as starvation, can influence these factors (Kawarabata et al. 1980, Pritchett et al. 1982). But we need to know more about the environment of the gut lumen; about how that environment fluctuates; and especially about those conditions that affect the ability of gypsy moth digestive fluids to dissolve PIBs.

With the dissolution of the PIB matrix protein, enveloped nucleocapsids are released in the gut lumen. Many of the nucleocapsids are carried with the food through the alimentary system and are defecated. But some nucleocapsids apparently find their way into the hemocoel. Exactly how nucleocapsids penetrate the peritrophic membrane and pass through the gut epithelium into the hemocoel has not been determined. However, hemolymph bioassays

indicate that infectious viral material is in the hemocoel as early as two hours after ingestion of PIBs (Shields 1984a). Since virus is in the hemocoel so quickly, direct passage of inoculum nucleocapsids from the gut lumen to the hemocoel seems likely. This phenomenon has been reported for Autographa californica NPV in Trichoplusia ni (Granados and Lawler 1981).

For a systemic infection to proceed, once in the hemocoel, nucleocapsids must escape host defense mechanisms, enter susceptible cells, replicate, and progeny nucleocapsids must be released. Of the five types of hemocytes in gypsy moth larvae, three are susceptible to NPV infection - prohemocytes, plasmatocytes and especially coagulocytes. Coagulocytes are the first hemocytes to replicate virus and eventually are selectively depleted from the circulating hemocyte population. Granulocytes and spherulocytes do not seem to be susceptible to NPV.

Nucleocapsids appear to enter gypsy moth hemocytes by two routes. One is by fusion of the viral envelope with the hemocyte plasma membrane, releasing the nucleocapsid into the cytoplasm. Enveloped nucleocapsids also enter hemocytes by viropexis, an engulfment process. The fate of enveloped nucleocapsids that are engulfed is not certain. The vesicles containing the nucleocapsids may fuse with lysosomes and the nucleocapsids may be destroyed (Adams et al. 1977). However, it is possible that the virus might utilize this process for entry and subsequent release into the cytoplasm.

Nonenveloped nucleocapsids in the cytoplasm frequently are in close alignment with microtubules. This association has been observed in other NPV-host systems (Granados 1978, Granados and Lawler 1981) and Granados (1978) has suggested that microtubules might be involved in the movement of nucleocapsids from the cell surface to the nucleus. In some gypsy moth hemocytes, arrays of nucleocapsids and microtubules appear to extend from the cytoplasm into the nucleus (Shields 1984a, 1984b).

Virus morphogenesis in gypsy moth hemocytes is similar to that reported for NPVs in other species (Paschke and Summers 1975, Granados 1980). Nucleocapsids that acquire envelopes within the nucleus are occluded by polymerizing protein, forming PIBs. Increasing numbers of PIBs are seen in hemocytes during the course of the disease, but hemocytes do not produce as many PIBs as do the cells of the fat body (Shields 1984a).

Infection is seen in the fat body much later than in hemocytes, but eventually all of the cells of the fat body seem to be virus-infected. Nearly all of the nucleocapsids produced in fat body cells are enveloped in the nucleus and occluded. Very large numbers of PIBs are produced and few, if any, nucleocapsids are released from fat body cells.

In contrast, hemocytes replicate and release nucleocapsids into the hemocoel throughout the course of the disease. Nonenveloped nucleocapsids bud from hemocyte nuclei in long tubules of nuclear envelope. They may be released into the hemocoel by fusion of the

¹This is part of a dissertation prepared as part of the requirements for the Ph.D. degree, presented by the University of Connecticut, Storrs.

plasma membrane and outer lamella of the tubules, as was suggested by Nappi and Hammill (1975). Or, they might first be released into the cell cytoplasm through breaks in the tubule lamellae. In any case, many nonenveloped nucleocapsids are in the cytoplasm of infected hemocytes, and many of these nucleocapsids bud through the plasma membrane into the hemocoel. In so doing, they acquire a peplomer-modified envelope derived from the hemocyte plasma membrane. Adams et al. (1977) suggested that enveloped nucleocapsids bearing peplomers are responsible for secondary infection. If so, hemocytes play an important role in intercellular transmission of virus.

Little is known about the effectiveness of gypsy moth defense mechanisms against NPV, or about how changes in host metabolism might affect susceptibility to infection. A recent study shows that gypsy moth larvae, parasitized five days previously by Blepharipa pratensis, are resistant to NPV. Perhaps B. pratensis myiasis activates anti-viral substances in the hemolymph of the host.

More research is needed on all of the factors that might be involved in determining whether NPV will invade and kill the gypsy moth. Such information is necessary for prediction of viral epizootics and also could be useful in the development of improved viral pesticides.

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²Unpublished data, on file, Center for Biological Control of Northeastern Forest Insects & Diseases, Hamden, Connecticut.

Enzyme Immunoassays for Detection of Gypsy Moth Nuclear Polyhedrosis Virus

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Abstract

Enzyme-linked immunosorbent assays (ELISA) were developed for detecting gypsy moth (*Lymantria dispar* L.) nuclear polyhedrosis virus (NPV). They were used to detect the presence of NPV in hemolymph samples collected from infected larvae. The incorporation of hybridoma antibodies with these procedures would make them even more specific for gypsy moth NPV detection. A pilot study of evaluating NPV spray with ELISA is also presented here. Potentially, these immunochemical methods have important applications in an IPM approach toward the control of gypsy moth.

Introduction

Nuclear polyhedrosis virus of the gypsy moth has received considerable attention as a biological control agent because it is (1) selective for lymantriids, (2) environmentally safe, (3) endemic among natural populations, and (4) persistent in the field after its introduction into a population (Doane 1970, Podgwaite and Campbell 1971, Lewis and Etter 1978, and Lewis 1981). With the recent registration of the European sawfly virus (Neochek) by the Environmental Protection Agency, there are four insect viruses (gypsy moth, Douglas-fir tussock moth and *Heliothis* NPVs) that need to be examined carefully as how they could fit into integrated pest management schemes of these important pests.

Detection of the gypsy moth nuclear polyhedrosis virus

In order to evaluate effectively the potential of these NPVs for controlling insects, reliable bioassays and analytical methods are needed for both laboratory and field studies. Numerous bioassay procedures have been developed for assaying the presence and the virulence of gypsy moth NPV. One of the disadvantage of bioassay is the long incubation time, usually 10-15 days, required to show any disease symptoms. During this time, polyhedral inclusion bodies (PIBs) can be seen as refractile particles, 1-10 microns in diameter, in the larval hemolymph. Microscopic identification of PIBs could shorten the diagnostic time. However, this method is only reliable in cases of acute

infection. When microscopic diagnosis is performed in early stages (viruses present mostly in the non-occluded form) and low levels of larval infection, there is the possible difficulty of distinguishing a few PIBs from other particulate materials in the hemolymph.

Dubois (1981) reported that refractometer measurements of the hemolymph could be used to detect the presence of virus. Quantitative prediction of virus mortality could be made with accuracy in third instar larvae. However, this method is rather stadium-specific, since accuracy cannot be assured with fourth and fifth instars. Larvae just prior and after ecdysis and sample size of the first two instars also present problems for analysis.

Enzyme-linked immunosorbent assay (ELISA), since its development by Engvall and Perlmann (1971, 1972), has received wide application in the biological sciences. This method involves the detection of an antigen with enzyme labelled antibodies. The antigen-antibody complex is then detected by the enzyme label which changes the color of added substrate. The results are presented in the form of a quantitative optical density measurement. The advantages of ELISA over other immunochemical methods include: (1) fast test results (3-4 hrs), (2) simple colorimetric end point, (3) specificity for a given antigen, and (4) extreme sensitivity and reliability. ELISA methods have already received wide applications in modern agricultural research, particularly in diagnostics and epidemiological studies of plant and animal diseases. In recent years, different ELISA methods have been employed for the detection of insect baculoviruses (Kelly et al. 1978, Crook and Payne 1980, Longworth and Carey 1980, Langridge et al. 1981, Evans et al. 1981, Volkman and Falcon 1982). ELISA will undoubtedly be used more extensively in insect control programs involving microbials in the future.

Development of ELISA for gypsy moth NPV detection

Preparation of Specific Antibodies

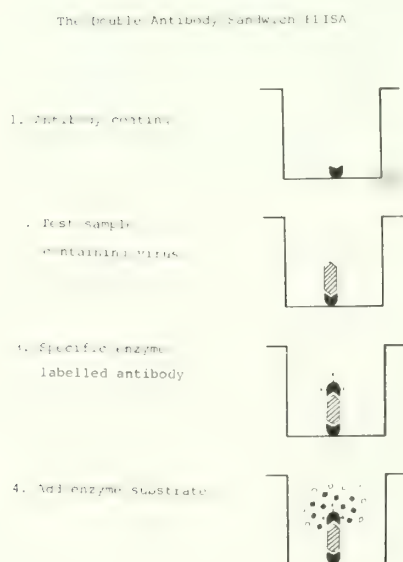
The most important requirement for an ELISA method is the development of a high titer antiserum against a purified preparation of antigen. Gypsy moth NPV PIBs were purified from moribund larvae following the procedure of Tompkins et al. (1981). Whole PIBs were dissociated in 0.1M Na₂CO₃ at pH 11 for 30 minutes, followed by pH adjustment to 7.3 with 2N HCl. New Zealand white rabbits and guinea pigs were immunized for antisera production. Antisera were only accepted if they detect 1 ug/ml of NPV at 1:10⁵

dilution. Immunoglobulin (IgGs) was purified by Protein A chromatography (Goding 1978) and the IgG concentration estimated spectrophotometrically with an extinction coefficient of 1.8 at 280 nm (McGuigan and Eisen 1968). The purification procedure is important for the production of antibody-enzyme conjugates with high specific activity and precision in the development of ELISA methods.

The Double Antibody Sandwich Method

Purified antibodies specific to the virus are coated or adsorbed onto a solid surface such as the well of a polystyrene or polyvinyl 96-well microplate (Fig. 1). A test sample, suspected to contain the viral antigen, is incubated with the antibody sensitized wells. All the hemolymph samples collected are first treated with pH 11 buffer followed by neutralization with acid. The viral antigens, polyhedrin and virions, are bound to antibodies developed with dissolved polyhedra. Enzyme-labelled specific antibodies are added after the test sample is removed. The antigen is sandwiched between two antibodies and the whole complex is bound to the surface of the well non-covalently. After a period of incubation, the enzyme conjugate is removed and is followed by the addition of the substrate. The color intensity is directly proportional to the amount of enzyme present in the sandwich complex, which in turn is proportional to the amount of virus present.

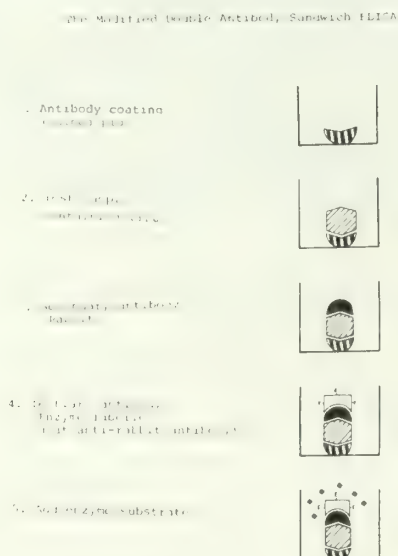
FIGURE 1



The Modified Double Antibody Sandwich Method

This method involves the development of antisera from 2 different animals (Fig. 2). The antibody used to sensitize the well is referred to as the primary antibody. After the addition of the test sample, antisera developed against the virus in a different animal is introduced. This is referred to as a secondary antibody. The virus is sandwiched between antibodies from two different animals. In the current studies, guinea pigs and rabbits were used. At this stage, either antiserum could be used as the primary antibody so long as the enzyme-antibody conjugate is directed at the secondary antibody. The antibody conjugated to the enzyme is referred to as the tertiary antibody which can be either goat anti-guinea pig or anti-rabbit antibody. These tertiary antibodies can be conveniently obtained from many commercial sources. When the sensitivity of the two ELISA methods are compared, the modified double antibody sandwich method is shown to be more sensitive. Detection limit of 50 ng/ml can be obtained consistently with the modified double antibody sandwich method. Since a secondary antibody is used, more than one enzyme-labelled tertiary antibody would link to the sandwich complex. With the presence of more enzymes present in the complex, the detection sensitivity is increased as a result.

FIGURE 2



Plastic Bead ELISA

Despite the advantages of ELISA, it has not received wide acceptance in virus epizootiological studies because most field researchers usually lack the equipment or expertise to perform microplate ELISA

procedures. Hendry and Herrman (1980) have employed plastic beads as adsorptive solid phases for protein antigens. In the laboratory for this study (Ma et al. 1984), the relative merits of polystyrene and nylon beads were compared. The polystyrene bead was used in place of a microplate for ELISA detection of gypsy moth NPV (Fig. 3). The protocols developed for double antibody sandwich and modified double antibody sandwich ELISA can be easily adapted to the plastic bead procedure. There are several advantages in using plastic beads: (1) simple protocol which does not involve specialized equipment, (2) plastic beads are easily washed and ready for reuse. Cost is reduced considerably compared to that of disposable microplates. However, this method is not able to handle a large number of test samples which might be a disadvantage in certain situations.

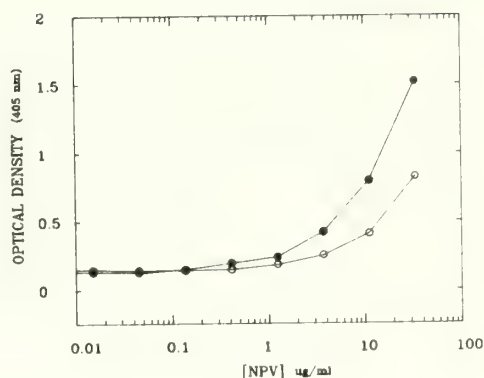
FIGURE 3



Detection of NPV in Infected Gypsy Moth Larvae

When we compared the sensitivity of the double antibody sandwich ELISA between the dissociated virus and whole polyhedra as antigenic preparations, the results showed that better sensitivity can be achieved when the virus test sample is subjected to alkaline dissociation followed by pH neutralization (Fig. 4). There are two possible reasons for this result. (1) When the antigen is in the dissociated

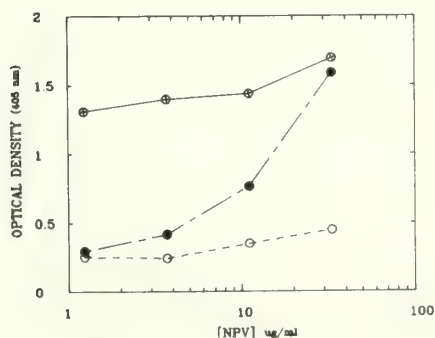
FIGURE 4



form, the antibodies recognize the epitopes of both the polyhedral and viral proteins. However, only those antibodies that recognize the surface epitopes of the polyhedra will react with the whole inclusions. (2) The affinity of proteins to the microplates is mainly a hydrophobic-hydrophilic type interaction. Since there are repeated washings in an ELISA protocol, some of the denser polyhedra may be washed off. A dissociated virus preparation consists of smaller protein fragments which would result in stronger attachments.

In order to look at the feasibility of ELISA for the detection of NPV in insects, the following experiment was performed. Fourth instar gypsy moth averaging 100 mg were used as experimental animals. Lewis et al (1981) reported that the LC_{50} for early 4th instar larvae was found to be approximately 10^5 PIBs for the Pennsylvannia strain larvae. Ten 4th instar larvae were fed with a lethal dose of 10^6 PIBs/larva and all the hemolymph

FIGURE 5



samples were collected and checked for NPV with the double antibody sandwich method after one week. A negative control was provided by taking hemolymph from non-infected larvae at about the same age and assaying them for virus. The colorimetric reading of infected hemolymph, at 1:3 dilution, was found to be approximately one optical unit higher than the non-infected samples (Fig. 5). When the larvae were monitored at different times after ingesting a lethal dose of PIBs, the double antibody sandwich method can detect NPV in the hemolymph as early as three days post infection.

Case Study: Evaluation of Gypsy Moth NPV Field Application with ELISA

Dr. Tim Tignor (Department of Conservation and Economic Development, Division of Forestry, Virginia) conducted a pilot study on the evaluation of NPV spray applied to shade trees in 1983. Twenty white oaks (*Quercus alba* L.) on a small portion of the Conway-Robinson State Forest in Prince Williams County, Virginia were chosen for the evaluation of gypsy moth NPV spray. Trees ranged in size from 3.1 to 10.8 inches DBH and about 25 to 45 feet in height. Gypsy moth larvae were extremely difficult to find. Test trees were essentially uninfested. Larvae for spray treatment evaluation were reared from egg masses collected near the northern Virginia/West Virginia border along U.S. Route 9 as the eggs were hatching on April 19. Larvae were held in the laboratory and fed with fresh oak leaves until most were second instars. On the afternoon of May 9, 200 larvae were placed about 20 feet above ground on each of the 20 test trees. Another 100 larvae per tree were added on the morning of May 12. Larvae were distributed among several branches.

Gypsy moth NPV was applied with a hydraulic sprayer to ten test trees on May 12th. Spray formulation consisted of 5.95 lbs of NPV powder blended well with a small portion of water and added to a larger volume of water containing 2 gallons of Rhoplex B60 A sticker, followed by 20 gallons of feed grade molasses and enough water to make 100 gallons. The virus concentration calculated to be approximately 5×10^7 PIBs/ml. Separation of treated and untreated trees ranged from about 50 to 500 feet.

TABLE 1. Numbers of larvae and pupae under burlap bands on NPV sprayed and unsprayed trees.

Date	5/18	5/23	5/26	6/3	6/9	6/16	6/23	6/30	7/7	7/15	7/21
Sprayed	23	32	28	0	0	0	0	1	0	0	2
Unsprayed	91	176	355	139	105	50	30	18	3	0	1

* Larvae on 6 of 10 trees; total number estimated.

Counts of larvae and pupae found under the burlap bands are shown in Table 1. Differences in larval numbers between sprayed and unsprayed trees were readily apparent from the first count on May 18. Larvae were noted on most sprayed trees throughout June, but none was found on sprayed trees during this period. After May 26, mean larval numbers declined steadily, and pupae were found on only a few trees. On May 26, all larvae under burlap bands were collected and frozen for later analysis by modified double antibody sandwich procedure described previously. One hundred larvae reared to the third instar were also tested for virus. Table 2 summarized the results. Larvae held in the laboratory yielded negative results. Only 18% of the larvae from untreated trees were infected compared to 64% of larvae from treated trees. When arbitrary categories were chosen to rank levels of infection, the difference between treatment and control groups was still greater. The heavily infected larvae have up to 50 ug/ml of virus. It is important to note that the survivors from the sprayed trees exhibit a higher level of infection. Most of these larvae would probably be dead and become a source of virus dissemination. The source of virus detected in insects from the unsprayed trees may be due to NPV drift from sprayed trees or possibly the breaking of "virus latency" under environmental stress.

TABLE 2 Virus infection levels of larvae from NPV sprayed and unsprayed trees as determined by the modified ELISA technique.

Infection Level ^{1/}	Percent of Larvae ^{2/}		
	Sprayed	Unsprayed	Laboratory
None	36	82	100
Light	14	9	0
Moderate	11	2	0
Heavy	0	1	0
Very Heavy	39	6	0

^{1/} Positive infection levels arbitrarily assigned to consecutively increasing optical density ranges of .05 units each.

^{2/} Numbers of larvae sampled: sprayed = 28, unsprayed = 292, laboratory = 100.

Development of Hybridoma Antibodies for the Gypsy Moth NPV

Limitations of Polyclonal Antibodies

ELISA may even be used as a quantitative tool in cases where the virus preparation is positively identified as gypsy moth NPV. Caution is advised because baculoviruses are shown to share similar antigenic characteristics using different serological methods such as radioimmunoassay, complement fixation and immunoprecipitin tests (Bilimoria et al 1974, Elliot et al 1977, and Carey et al. 1978). The presence of heterologous NPV virus in the test sample may be interpreted

as a small amount of gypsy moth NPV. However, there are examples of successes in using ELISA for diagnosis of viruses. Crook and Payne (1980) showed that ELISA can discriminate granulosus virus from Pieris brassicae, Agrotis segetum, and Cydis pomonella. ELISA is also capable of distinguishing plant viruses which have been shown to have serological relationships by Ouchterlony double diffusion (Lister and Rochow, 1979, and Koenig 1978).

Since gypsy moth NPV is known to be specific for lymantriids only, it is therefore safe to assume that the hemolymph samples collected from infected larvae will yield positive readings only if the gypsy moth NPV is present. If we need to perform experiments such as the environmental persistence of NPV, an antibody preparation that is specific only to the gypsy moth is vital.

Rationale of Developing Hybridoma Antibodies to Gypsy Moth NPV

Conventional serological methods have been shown to be unreliable for the identification of Lepidopteran NPV (Hohmann and Faulkner 1983). The polyhedrin protein of these viruses share a lot of similar antigenic determinants. The antisera used in these studies involved the use of polyclonal antibodies which is a mixture of immunoglobulins to all the epitopes of an antigen. If two different antigens have a portion of the epitopes that are similar, crossreactivity would result.

Kohler and Milstein (1975) developed a method of making monoclonal antibodies that would only bind to one epitope. It is possible to develop specific biological probes for epitopes that are unique for that antigen. These antibodies are generated by somatic cell hybridization of mouse splenocytes and myeloma cells with polyethylene glycol which would result in the establishment of specific antibody producing cell lines. Each hybrid cell line synthesizes a homogeneous antibody that is highly specific for a single antigenic determinant or epitope (Yelton and Scharff 1981). This technology has the potential of locating antigenic determinants or epitopes that are unique for a particular antigen. In this case, monoclonal antibodies developed against these sites would be valuable for diagnostic work and the systematics of NPVs.

In our laboratory, 35 different hybridoma cell lines producing monoclonal antibodies have been developed to the purified polyhedra of gypsy moth. We are in the process of characterizing these hybridoma antibodies as to their immunoglobulin subclasses and affinity to

the antigen. To pick out the monoclonal antibodies specific to the gypsy moth, at least two crossreactivity tests against other lepidopteran NPVs found in the forest ecosystem will be performed.

The first test involves the use of indirect ELISA to screen all the gypsy moth NPV monoclonal antibodies against purified preparations of European sawfly, tussock moth, spruce budworm and other NPVs found in forest environment. The second method, referred to as Western blotting, involves the separation of the purified polyhedra proteins of other NPVs using gel electrophoresis, followed by horizontal transfer of proteins from gel to a nitrocellulose membrane. The membrane would then be incubated with the monoclonal antibodies developed for the gypsy moth NPV followed by histochemical staining to visualize the actual binding sites. If a clone of gypsy moth monoclonal antibodies binds only to the gypsy moth viral protein, these tests would confirm that a specific biological probe for a type specific antigenic determinant is located for the gypsy moth NPV.

Prospectus

The study of the gypsy moth nuclear polyhedrosis is important because of its effect on population dynamics and the decision to use Gypcheck as a possible component in an integrated management program. ELISA offers immediate help in studies involving the surveying of virus in gypsy moth populations, quality control of virus formulation, and the evaluation of NPV sprays.

There are additional important questions that need to be answered such as the elucidation of epizootiology, the environmental persistence and dissemination pattern of this NPV. Intelligent decision involving virus applications would be difficult if these basic knowledge are lacking. The development of a reliable protocol for environmental sampling of soil, host plant and non-target hosts would be an important step towards answering these questions. Solid phase radioimmunoassay will have to be developed because it offers the sensitivity of detection down to a few polyhedral inclusion bodies. Hybridoma antibodies will be incorporated in both radioimmunoassay and ELISA procedures to ensure specific detection of gypsy moth NPV and not other NPVs that might be present in the forest ecosystem. I am a strong believer that a lot of the procedure developed in this gypsy moth program will become standard protocols in many insect control programs involving microbials in the future.

Acknowledgement

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Recent advances in genetics and molecular biology make possible the cloning and genetic manipulation of genes for insecticidal activities from natural insect pathogens. Using recombinant DNA methods and site-directed mutagenesis of specific gene regions, production of new and improved biorationals should be possible.

In recent years the agricultural pesticide industry, currently generating the equivalent of more than 13 billion U.S. dollars in world-wide sales, has been fraught with a number of problems that in the aggregate have led both manufacturers and consumers to seriously examine the future trends of the industry. These problems include the acute and chronic toxicities of many pesticides to man and other animals, lack of specificity (killing of desirable insect species and natural predators), rapid development of resistant insects under intensive usage, rapidly escalating production costs, and disposal problems of often-toxic residues and by-products. Increased pressures from environmental groups and governmental regulatory agencies have led to the banning of chemicals such as DDT, 2-4-D, Mirex, EDB and various others (especially chlorinated hydrocarbons) from the pesticide marketplace. One solution to these problems is to develop new pesticides which are safer to use, more specific to target insects, weeds, and plant disease organisms, and non-polluting to the environment. The most obvious alternative to chemical pesticides is the so-called biorationals. Such a class of pesticides has been known for some years and includes a variety of insect-pathogenic bacteria, viruses, and fungi. In addition, there is a variety of protozoans, predators and parasites, growth regulators, and pheromones which show potential as biological pesticides.

Despite their many desirable properties, the list of biological pesticides and related biorationals currently registered for use is distressingly small (Miller *et al.*, 1983). The major product, by far, is *Bacillus thuringiensis* (BT), a sporulating bacterium that produces a crystalline toxic protein active on many lepidopterous (caterpillar) insects. United States sales of BT in 1982 were about \$10M -- world-wide they approach ~\$20M. A variant of BT, called BTI, has recently been licensed for control of several species of disease-carrying mosquitos and black-flies. Three other related bacteria, *Bacillus popilliae*, *Bacillus sphaericus*, and *Bacillus penetrans*, are of more limited use. *B. popilliae*

(sold in the U.S. under the trade name Doom) has activity on Japanese beetles and related species and has a small market. *B. sphaericus* is highly pathogenic to mosquitos but to date has only been used experimentally. *B. penetrans* has potential for control of root-knot nematodes and root lesions, but so far has only been tested in greenhouse conditions. Biopesticides of viral origin include Elcar, used for control of *Heliothis* larvae, Gypchek, a virus for control of gypsy moth, and an as-yet unregistered virus which has considerable potential for control of codling moths on a variety of fruit and nut trees, as well as for tip moth control on pine trees. Fungal agents for insect control include a single product in the United States (Mycar, registered for citrus mite control in Florida) and two *Verticillium* species registered in the United Kingdom for control of aphids and white flies on glasshouse crops. Two fungal products have recently been licensed for weed control in the U.S.: Devine, used for control of strangler weed in Florida citrus groves, and Collego, a fungus licensed for use on northern jointvetch in soybeans and corn.

The only other biorational products of any significance in the agrichemical market are pheromones, attractants, and hormones. Gossyplure is a pheromone of *Heliothis* (cotton bollworm) that is used fairly extensively as a mating confusion spray in the southwestern United States, Mexico, Brazil, and Egypt. Dimilin is a growth inhibitor that has recently been registered for use on cotton and on forest trees.

Although all of these products are effective when used properly, they have distinct drawbacks which limit user acceptability. The bacterial and viral agents must be ingested to be active, and their killing action, especially the viruses, is slower than conventional chemical insecticides. These agents are also subject to rapid inactivation by exposure to sunlight and are readily washed off the foliage by rain. Viral products are expensive to produce since current methods require propagation in living insect larvae. Fungi are very intolerant of low humidity conditions or high temperature, and thus are generally used only in greenhouses or in cool climates. All of these agents require more user sophistication to be effective than is commonly encountered among growers.

Clearly, the array of effective biological pesticides developed to date is not extensive. While many of these biorationals have been known for some time, their aggregate market share of the total pesticide industry has remained relatively insignificant, for several reasons. Chief among them has been a lack of understanding of their basic properties, including their synthesis and mode of action. As an example, consider the bacterial insecticide BT. Although BT has been marketed as an insecticide since the late-1950's, the nature of its insecticidal toxicity came under study only several years later and is still not fully understood. Genetic analyses of the production of the insecticidal toxin were not

even initiated until the late 1970's, and are just now beginning to reveal where the toxin genes are localized and how they are expressed. For other biologicals the level of our basic understanding of their inheritance and mode of action is considerably less. Without detailed knowledge of their mechanisms, it is not surprising that efforts to develop these agents as alternatives to more conventional pesticides have been sporadic at best.

Despite the limitations and disadvantages of these biorational products, there is currently a great deal of interest, both from the basic science viewpoint as well as from the commercial side, in agents such as BT. A number of laboratories in the U.S. and abroad are currently focusing their attention on the genetics and molecular biology of BT and other biological pathogens, including other bacteria, viruses, and fungi. In addition, a number of new start-up biotechnology companies have announced plans to direct significant fractions of their efforts to development of new and improved biological pesticides. One such company is Ecogen, Inc., founded just a few months ago in Princeton, N.J., and with which I am especially familiar since I have recently agreed to become their full-time director of research and development beginning on June 1 of this year. The major thrust of Ecogen, Inc. will be to apply a multidisciplinary, integrated approach to the development of novel biopesticides, using modern technologies of genetics, protein chemistry, immunology, and cell biology.

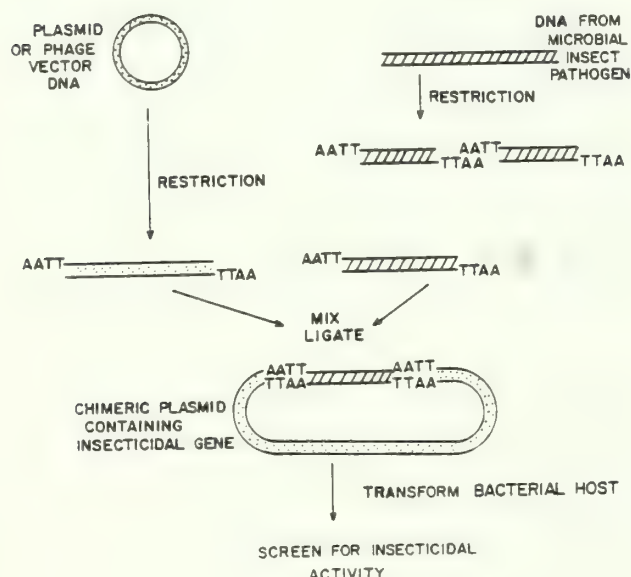


Fig. 1 Gene-splicing technology for molecular cloning of insecticidal genes.

What factors have led to the resurgence in interest in biological pesticides? Other than economic and environmental considerations, probably the major technological advance that has contributed to interest in biorationals is that of recombinant DNA-gene splicing methodology (Fig. 1). There are two factors of importance in this methodology. First is the ability to isolate a gene (or cluster of genes) controlling a given activity (e.g. pesticide synthesis) from the vast background of other genes and activities in any organism, regardless of its genetic complexity. Thus, in principle, a gene from a fungal cell can potentially be isolated (cloned) and its structure and regulation studied as easily as that of a bacterial gene. Second, once a gene has been isolated by molecular cloning, its structure can be readily altered (mutated) by a variety of molecular tricks that would be impossible by conventional mutagenesis procedures using intact organisms. For example, digestion of cloned genes with a combination of restriction endonucleases (enzymes which recognize and cleave specific 4- or 6-base sequences in DNA) identifies sites which can be specifically mutated by one of several methodologies recently developed for site-specific mutagenesis (Figs. 2 and 3).

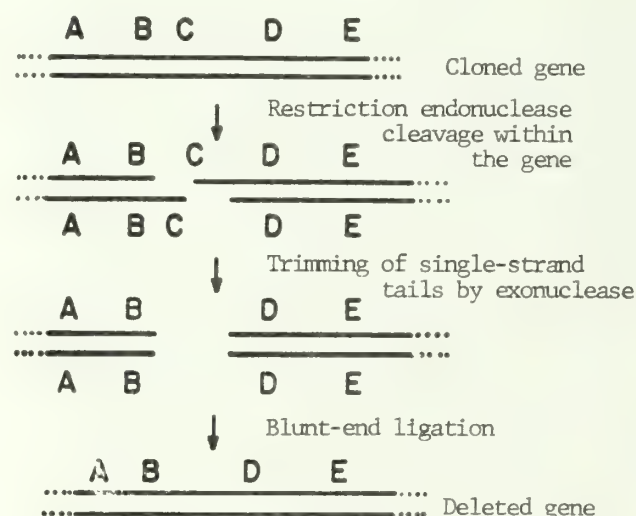


Fig. 2 Generation of deletions in an insecticidal gene.

These treatments can be carried out on a cloned gene *in vitro* (i.e., in a test tube) with much greater efficiencies than could be accomplished *in vivo* (in the intact organism). By these techniques one can thus change single bases in a DNA gene, delete blocks of bases, or add segments of DNA at will and observe the effects on expression of the gene. While these changes might also occur spontaneously *in vivo* for a non-cloned gene, their frequencies would be orders of magnitude less and their detection would be exceedingly difficult. Thus, the techniques of

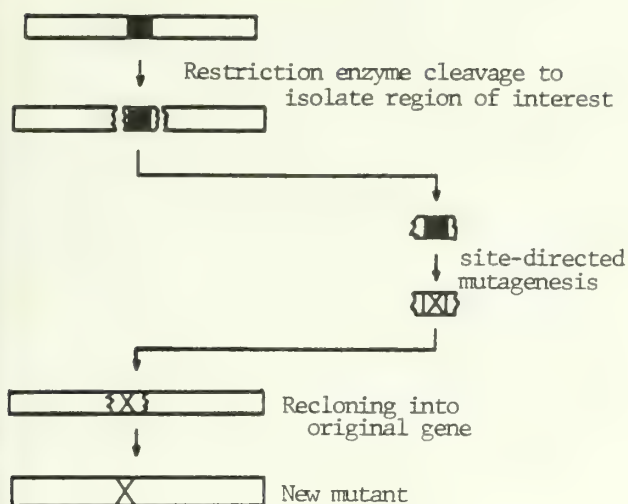


Fig. 3 Site-directed *in vitro* mutagenesis.

modern molecular cloning serve to greatly enhance the genetic sensitivity of mutational approaches. The isolation of individual genes by molecular cloning also makes possible the enhanced production of their products (usually enzymes or other proteins) by genetically fusing them to highly-efficient regulatory sequences (promoters). In certain instances, this manipulation can elevate a gene's expression several hundred-fold above its normal level of activity. Further, a gene which normally produces its protein product inside the cell, often a self-limiting process, can be fused to a small signal peptide coding sequence which allows the protein to be transported outside the cell. This construction can both increase the level of production of a particular gene product as well as facilitate its recovery because it is transported to the external medium.

How can the types of genetic manipulation described above be applied to the improvement and commercialization of biological pesticides? The possibilities are numerous. For example, molecular cloning of a gene which specifies an insecticidal toxin protein makes it amenable to yield enhancement by attaching the gene to a high-efficiency promoter sequence, thereby markedly increasing the yield. The gene can also be altered by site-directed mutagenesis procedures to either broaden the spectrum of targets (e.g., different insects it will attack) or to increase its activity on a specific target. Cloning of two or more genes for distinct pesticide activities into the same host cell could generate a multi-purpose pesticide, having activities against two or more very different targets (e.g., two different insects, an insect and a weed, an insect and fungal disease, etc.). The relative ease with which such different gene combinations can be potentially constructed by recombinant DNA technology makes the possibilities virtually unlimited. The limitations fall to the imagination of the researcher and to the sensitivity of detection methods for identifying new gene combinations of interest amongst a background of

hundreds, or even thousands, or new variants. In *Bacillus thuringiensis*, the discovery in our laboratories (González *et al* 1982) of a natural, highly-efficient plasmid exchange system opens the way for constructing strains having novel combinations of insecticidal genes from different strains of BT, or other related strains. This plasmid transfer system has already been used to construct strains of BT having two toxin-coding plasmids from different parental origins, as well as to convert strains of normally non-toxic *B. cereus* into BT-like variants. These and other methodologies offer the possibility for producing new pesticides that can be rapidly tailored to individual locales and situations. For example, predictions of an outbreak of a particular plant disease and concomitant infestation of a particular insect on some important crop could dictate the construction of a bacterial, viral or fungal strain having the capabilities to control both pests. For some other crop or locale, a different combination might be called for. This type of rapid response to changing pest problems would be a significant departure from current planning in the pesticide field, which must be done years in advance due to the time required to develop new products.

Another future innovation in biological pesticides, as previously mentioned, is the possibility for creating pathogens having two different activities in the same strain. Smith, *et al* (1983) have recently shown that the genome of AcNPV, a baculovirus with insecticidal activity, can be used as a cloning vector into which foreign genes can be inserted and subsequently propagated and expressed in cultured insect cells. In the first experiments the gene they cloned was human β interferon, an anti-viral protein which is being clinically tested for activity on a variety of disease-causing viruses as well as for possible anti-cancer activity. Remarkably, the amount of interferon produced by the insect cell clones was much higher than that produced by *E. coli* bacterial cells, the most common host for propagation of cloned genes. This virus may be potentially useful in the future for cloning genes for BT toxins, generating a bifunctional pathogen having two distinctly different pathogenic activities directed at the same target insects.

Perhaps the ultimate accomplishment in developing new biological pesticides would involve incorporating their genes directly into the genome of a susceptible organism, thereby conferring the ability to synthesize its own pesticide and totally eliminating the usual delivery system. For example, it may be possible to transfer genes for bacterial insecticide toxins directly into the genetic backgrounds of various plants, enabling them to synthesize their own insecticidal material and bypassing the costly need for repeated sprayings. Genetic manipulations of this type may already be technically possible.

The soil bacterium *Agrobacterium tumefaciens* harbors Ti plasmids with potential as natural

vectors for the transfer of foreign DNA into plant cells (Chilton, 1983). Upon infection of a susceptible plant the bacterium induces formation of a crown gall tumor. Crown gall tissues synthesize a group of novel metabolites called opines, which are specified by the high molecular weight Ti plasmids in the *Agrobacterium* strain. Using modified Ti plasmids deleted in many or all of their tumorigenic functions it is now possible to molecularly clone a variety of homologous and heterologous gene functions and to express them in plant cells (Zambryski et al, 1983). Advances in the regeneration of whole plants from callus tissue derived from transformed plant cells promise to greatly expand the spectrum of plant and foreign gene combinations which can be constructed. The introduction of toxin-specifying genes from *Bacillus thuringiensis* and other microbial pathogens directly into plants may thus be possible in the very near future. Both plant viruses and bacterial vectors are already known which show promise for transporting foreign genes into plant cells. While many technical difficulties still remain to be overcome in accomplishing many of the suggested goals, it seems clear that the pesticide industry is poised on the threshold of a new era in its history.

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DEVELOPMENTS IN COMMERCIALY PRODUCED

MICROBIALS AT BIOCHEM PRODUCTS

John Lublinkhof, Ph.D. and Douglas H. Ross, Ph.D.

Technical Manager and Marketing Manager,
respectively. Biochem Products, Montchanin,
DE 19710

Biochem Products is part of a large industrial and scientific family - the Solvay Group. Solvay, headquartered in Brussels, Belgium is a multinational company with 46,000 employees worldwide. In the U.S., our working partners include a large polymer manufacturer, a peroxygen producer and a leading poultry and animal health products company. Biochem Products is a division of the latter - Salsbury Laboratories, Inc. Biochem Products in the U.S. was started in 1979. It is committed to research, development and marketing of microbial products for insect pest management. Our first product was Bactospeine® Wettable Powder. Then we obtained a registration for Bactimos™ Wettable Powder (our B.t.i. product). Since then, we have concentrated our efforts at developing and marketing various formulations of each.

With regards to forestry, we initially acquired Novabac-3 from another company and developed the Canadian registration of this product for use against the spruce budworm in forests and woodlands. This product contains 32 BIU per U.S. gallon. The registration was obtained in 1981. At the same time, we were developing a modified liquid formulation of B.t. in the U.S. known as Bactospeine Flowable Concentrate. Bactospeine FC contains 35 BIU per U.S. gallon. This product has a registration (registered in the U.S. in 1981) for use against approximately 40 different pests in forestry and agriculture including the spruce budworm and gypsy moth. In Canada, registration was received in early 1984 for Bactospeine-F (forestry) and Bactospeine-A (agriculture). In the past two years, our interests have been in reducing the total volume of spray mix required per acre and still achieve effective control. This objective has been achieved.

While the above were being developed, a cooperative research effort between Biochem Products and Environment Canada's Laurentian Forest Research Center led to the development of Futura® Flowable Concentrate. Futura contains 54.5 BIU per U.S. gallon. Futura is designed for effective low volume application. Highly successful and consistent results have been obtained with a 1.5 Liter per Hectare dosage rate in a total volume of 2.5 Liters per Hectare. Futura was registered in the U.S. in 1983 and in Canada in early 1984.

Future developments will be in undiluted applications of these products with the objective of providing economical and effective control.

COMMERCIAL PRODUCTION OF MICROBIALS BY REUTER
LABORATORIES, INC., FOR CONTROL OF THE GYPSY MOTH
AND THE SPRUCE BUDWORM.

L. D. OBENCHAIN

DIRECTOR OF RESEARCH AND DEVELOPMENT, REUTER
LABORATORIES, INC., 14540 JOHN MARSHALL HIGHWAY,
FAIRFAX, VA 22065

REUTER LABORATORIES ANNOUNCES ADDITIONS TO ITS
LINE OF MICROBIAL INSECTICIDES WITH THE 1984-85
INTRODUCTION OF A BACILLUS THURINGIENSIS, BERLINER,
VARIETY KURSTAKI (HD-1, H-3A3B) WETTABLE POWDER
FORMULATION. GYPSY MOTH NUCLEOPOLYHEDROSIS VIRUS,
IN EXPERIMENTAL PRODUCTION SINCE 1982, IS SCHEDULED
FOR COMMERCIAL INTRODUCTION AS A WETTABLE POWDER IN
THE 1985-86 SEASON.

COMPANY HISTORY

REUTER LABORATORIES, INC., A VIRGINIA CORPORATION,
HAS PRODUCED MICROBIAL INSECTICIDES AND OTHER
BIOLOGICAL PRODUCTS SINCE ITS ORGANIZATION IN 1974.
ITS FIRST AND LARGEST SELLING PRODUCT IS MILKY SPORE
POWDER, COMPOSED OF THE BACTERIAL SPECIES BACILLUS
POPILLIAE DUTKY AND B. LENTIMORBUS DUTKY. IN THE
ABSENCE OF IN VITRO FERMENTATION METHODOLOGIES,
THESE BACTERIA MUST BE PRODUCED BY THE COLLECTION,
INOCULATION AND SUBSEQUENT INCUBATION OF THE WHITE
GRUBS OF THE JAPANESE BEETLE, POPILLIA JAPONICA
NEWMAN. THE ANNUAL PROCESSING OF THOUSANDS OF
JAPANESE BEETLE GRUBS REPRESENTS A CONSIDERABLE
INVESTMENT IN BOTH CAPITAL AND PROFESSIONAL EXPER-
IENCE AND IS THE BASIS FOR THE EXPANSION OF REUTER
LABORATORIES INTO OTHER MARKET AREAS. THE INTRODUC-
TION OF THE JAPANESE BEETLE SUPER TRAP, COMPLETE
WITH FLORAL AND SEX PHEROMONE ATTRACTANT BAITS,
HELPS HOME OWNERS, ON AN INDIVIDUAL OR COMMUNITY
BASIS, TO CONTROL JAPANESE BEETLE POPULATIONS WITH-
OUT THE USE OF CHEMICAL PESTICIDES.

IN 1980, REUTER LABORATORIES INTRODUCED A
PRODUCT CONTAINING NOSEMA LOCUSTAE CANNING SPORES,
A MICROSPORIDIAN DISEASE ORGANISM FOR THE CONTROL
OF CERTAIN GRASSHOPPERS AND CRICKETS, TO THE HOME
MARKET. SINCE 1981, THIS MICROBIAL INSECTICIDE
HAS BEEN FORMULATED BY REUTER IN THE FREEZE-DRIED
STATE, CRYOPRESERVED IN SERUM VIALS UNDER A NITROGEN
ATMOSPHERE. THE NOSEMA SPORES ARE REHYDRATED AT THE
POINT OF USE AND APPLIED TO A BRAN BAIT FOR THE CON-
TROL OF GRASSHOPPER OR CRICKET POPULATIONS ON SMALL
PLOTS, GARDENS OR AGRICULTURAL AND RANGELAND AREAS.

IN ITS FIRST VENTURE INTO FERMENTATION MICRO-
BIALS, BMC-BIOLOGICAL MOSQUITO CONTROL, A WETTABLE
POWDER FORMULATION OF BACILLUS THURINGIENSIS
BERLINER, VARIETY ISRAELENIS (H-14), WITH 1750
INTERNATIONAL UNITS OF ACTIVITY PER MILLIGRAM OF
FINISHED PRODUCT WAS INTRODUCED IN 1983 AND IS
CURRENTLY MARKETED TO THE HOME CONSUMER IN A 4
OUNCE PACKAGE.

IN OCTOBER, 1983, CONTROLLING INTEREST IN
REUTER LABORATORIES, INC., WAS ACQUIRED BY OTF
EQUITIES, INC., A PUBLICLY HELD COMPANY WHOSE
STOCK IS TRADED IN THE OVER-THE-COUNTER MARKET IN
THE DETROIT, MICHIGAN, AREA. UNDER NEW MANAGEMENT,
REUTER LABORATORIES HAS COMPLETED A PROGRAM OF
PRODUCT AND MARKET ANALYSIS AND HAS BEGUN THE CON-
STRUCTION OF EXPANDED OFFICE, INSECTARY, FERMENTA-
TION AND PRODUCTION FACILITIES. WITH THE APPLICA-
TION OF YEARS OF ACQUIRED EXPERIENCE AND EMPLOYMENT
OF ADDITIONAL PROFESSIONAL STAFF REUTER ANTICIPATES
THE INTRODUCTION OF AN EXPANDED LINE OF BIOLOGICAL
PEST CONTROL PRODUCTS.

BACILLUS THURINGIENSIS KURSTAKI WETTABLE POWDER

IN LATE 1984 REUTER LABORATORIES WILL RELEASE
A WETTABLE POWDER FORMULATION OF B. THURINGIENSIS,
BERLINER, VARIETY KURSTAKI (HD-1, H-3A3B) WITH
3200 INTERNATIONAL UNITS OF ACTIVITY PER MILLIGRAM
OF FINISHED PRODUCT. LABELS SUBMITTED TO EPA FOR
APPROVAL ARE IN FOUR COMMODITY AREAS:

1. BKT-VEGETABLE WORM AND CATEPILLAR CONTROL FOR
USE ON GREENHOUSE AND GARDEN VEGETABLES AND
FIELD CROPS,
2. BKT-LAWN MOTH CONTROL FOR USE AGAINST SOD WEB-
WORM AND RANGELAND CATEPILLARS,
3. BKT-FRUIT AND NUT TREE CATEPILLAR CONTROL, AND
4. BKT-SHADE TREE, ORNAMENTAL AND FLOWER CATEPILLAR
CONTROL.

THE LAST TWO LABELS WILL SPECIFICALLY TARGET GYPSY
MOTH LARVAE, AMONG OTHER APPROPRIATE LARVAL LEPIDOP-
TERAN SPECIES, WITH INITIAL TREATMENT RECOMMENDED
WHEN LARVAE ARE YOUNG AND LEAF EXPANSION IS AT THE
40% STAGE. RETREATMENT WILL BE RECOMMENDED 7 TO 10
DAYS LATER. UNDER APPROPRIATE CONDITIONS OF POPU-
LATION DENSITY AND AGE, THE SPRUCE BUDWORM WILL ALSO
BE TARGETED FOR CONTROL ON THE FOURTH LABEL.

GYPSY MOTH NUCLEOPOLYHEDROSIS VIRUS WETTABLE POWDER

INITIAL PRODUCTION OF A FREEZE DRIED GYPSY
MOTH NPV PRIMARY PRODUCT AT REUTER LABORATORIES
OCCURRED IN 1982. SUBSEQUENT RESEARCH EFFORTS HAVE
BEEN DIRECTED TOWARD PROPRIETARY IMPROVEMENTS IN
VARIOUS AREAS OF PRODUCTION AND FORMULATION. VIRUS
ACTIVITY IS EXPECTED TO BE MAXIMIZED BY CRYOGENIC
MILLING AND PRODUCT EFFECTIVENESS EXTENDED BY THE
USE OF NEW STICKING AGENTS AND UV PROTECTANTS.
FIELD TESTS OF THE REUTER GYPSY MOTH NPV PRODUCT
WERE SCHEDULED IN VIRGINIA FOR 1984 AS PART OF A
COOPERATIVE PROGRAM. THAT STUDY IS NOW RESCHEDULED
FOR 1985 DUE TO A SHORTAGE OF STATE FUNDS. PENDING
THE OUTCOME OF THESE FIELD TRIALS AND OTHER ECONOMIC
FACTORS, INTRODUCTION OF THE REUTER GYPSY MOTH VIRAL
INSECTICIDE IS ANTICIPATED FOR THE 1986 SEASON.

ECONOMIC CONSIDERATIONS FOR COMMERCIALIZATION

VIRAL INSECTICIDES DO NOT HAVE AN ENCOURAGING REPUTAION WITH RESPECT TO COMMERCIALIZATION. IN THIS RESPECT THE ORIENTATION OF THE REUTER LABORATORIES MARKETING PROGRAM MAY MEDIATE IN FAVOR OF THEIR DEVELOPMENT. DUE TO THE CYCLICAL NATURE OF GYPSY MOTH POPULATION EXPANSIONS AND CONTRACTIONS, INSECTARY AND PRODUCTION FACILITIES FULLY UTILIZED FOR GYPSY MOTH NPV MANUFACTURE DURING YEARS OF PEAK DEMAND WOULD BE UNDERUTILIZED IN THOSE YEARS WHEN THE POPULATIONS WERE LOW. IF VIRAL INSECTICIDES WITH SUBSTANTIAL GROWER AND HOME OWNER APPEAL, AS FOR EXAMPLE THE GRANULOSIS VIRUS OF THE CODLING MOTH, COULD BE DEVELOPED AND SUCCESSFULLY MARKETING TO BOTH OF THESE CONSUMER GROUPS, THEN THEY COULD BE MANUFACTURED DURING PERIODS OF MINIMAL DEMAND FOR THE GYPSY MOTH PRODUCT. THIS ALTERNATIVE USE OF PRODUCTION FACILITIES APPEARS TO BE AN ESSENTIAL FACTOR WHICH MAY ENSURE THE ECONOMIC VIABILITY OF GYPSY MOTH NPV PRODUCTION.

RECENT DEVELOPMENTS IN THE ZOECON CORPORATION
AND THE THURICIDE^R FORESTRY FORMULATIONS

William R. Beck

Product Development Representative
Zoecon Corporation, A Sandoz Company
Crop Protection Division
323 East Park Avenue, State College, PA 16803

Sandoz is pleased to announce the acquisition of Zoecon Incorporated of the United States and Canada. Effective November 15, 1983, all Zoecon and Sandoz Crop Protection Division personnel, facilities and products will be combined under the Zoecon, Inc. name. Zoecon will be a wholly owned subsidiary of Sandoz Ltd. with major offices in Palo Alto, Calif. and Dallas, Texas.

Thuricide^R forestry formulations will continue to be important products in the Zoecon product line. A. Temple Bowen will continue to handle government sales as the Thuricide Forestry Sales Manager for the United States and Lon Seymour will remain as product manager. Thuricide will be manufactured at our plant in Wasco, Calif. under the supervision of Tom Freaney.

William R. Beck, Product Development Representative, will continue to handle the forestry research and development in the northeast United States and eastern Canada.

In the past Sandoz has demonstrated the ability to combine its commercial expertise with government and university research programs in the development of innovative, environmentally safe products. This can best be illustrated by the diversity of the biological control agents that have been developed by Sandoz in recent years:

1. Elcar^R Microbial Insecticide is a formulation of the Heliothis nuclear-polyhedrosis virus (NPV), registered for suppression and control of the tobacco budworm (Heliothis virescens) and cotton bollworm (Heliothis zea). Elcar has no effect on beneficial arthropods found in the field.
2. CertanTM Bacterial Insecticide is a water dispersable concentrate of Bacillus thuringiensis Serotype 7 strain for the control of the Greater Wax Moth, Galleria mellonella. CertanTM has no detrimental effects on honey bees or honey production and the product may be applied directly to the honeycomb.
3. TeknarTM Biological Insecticide is a preparation of Bacillus thuringiensis Berliner, var. israelensis, Serotype H-14. It is selectively toxic to most species of mosquito larvae and blackfly larvae (Diptera: Culicidae and Simuliidae). Teknar is exempted from residue tolerance requirements and provides a unique opportunity for microbial control of mosquito and blackfly larvae

without harmful effects on humans, domestic animals, wildlife, beneficial insects, fish or other aquatic life.

4. Thuricide^R Microbial Insecticides are aqueous spray formulations based on the bacterium, Bacillus thuringiensis Berliner var. Kurstaki (b.t.) which is active against lepidopterous larvae, many of which are pests of shade trees and forests. Sandoz was the first company to successfully produce an aqueous formulation of b.t. capable of being applied by aerial application to the forest environment. Over the years Sandoz continued to improve the Thuricide formulation, progressing from the original Thuricide 16B to the present standard Thuricide 32LV and Thuricide 48LV formulations. This progression has resulted in formulations that can be pumped through aircraft systems undiluted and with sufficient atomization to provide excellent droplet spectrums and deposit on the target foliage. Thuricide formulations may also be diluted with any amount of water desired enabling the applicator to adjust the actual spray volume to meet his needs.

Zoecon will continue this tradition of innovative research and development of biological control agents for agriculture and forestry. This is evidenced by the recent development of the NRD-12 strain of Bacillus thuringiensis. Zoecon was the first company to successfully formulate and field test this strain as SAN415 against the spruce budworm in Maine in 1983. The success of this program has triggered an expansive testing program in forestry and agriculture in 1984.

In addition to the search for new more effective strains of b.t., Zoecon is continuing to develop new formulations of Thuricide. The success of the Thuricide 32LV and 48LV aqueous formulations has encouraged Zoecon to continue to develop more concentrated formulations. Research plans for 1984 include the testing of a 64 BIU per gallon aqueous formulation of b.t. These new more concentrated formulations have demonstrated the ability to be applied undiluted at low volumes providing improved efficacy while reducing the cost of application.

While the Zoecon corporation has placed its emphasis on biological control agents that are compatible with their fermentation technology, the company will continue to be receptive to other microbial agents that have the potential for commercial development.

As of November 15, Sandoz, Inc. Crop Protection in San Diego has moved to the Zoecon location in Palo Alto, Calif.

The new address and phone number for Thuricide are:

Zoecon Corporation
Crop Protection Division
425 Sherman Avenue
P. O. Box 10975
Palo Alto, CA 94303
(415) 857-1130

For more information regarding these products, please contact one of the Zoecon sales representatives listed below:

Lon Seymour
480 Camino Del Rio South
San Diego, CA 92108

Temple Bowen
23 Sherbrook St.
Augusta, Maine 04330

Dick Schneider
8048 Lincoln Way West
P. O. Box 243
St. Thomas, PA 17252

Paul Bystrak
R. R. #2
Box 137
Berrien Springs, MI 49103

We are looking forward to providing you with the quality product and service that has long been a tradition with Sandoz Ltd. and will now continue under the Zoecon banner in the United States and Canada.

SYMPOSIUM ON
FORMULATION AND APPLICATION OF MICROBIALS FOR
SPRUCE BUDWORM AND GYPSY MOTH CONTROL

J. A. Armstrong¹ and W. G. Yendol²

Introduction

This panel of experts from Canada and the United States has been brought together to discuss control techniques and strategies employed against these important defoliators - the spruce budworm and the gypsy moth. In selecting the panel we have chosen people with experience ranging from research to control. Our panel speakers are:

Bruce McGauley. - Supervisor, Pest Control Section, Ontario Ministry of Natural Resources. He will discuss the spruce budworm spray program in Ontario and the policies that government follows in organizing the spray program.

Michel Pelletier. - Quebec Ministry of Energy and Resources. He will speak about the spruce budworm program in Quebec, and the use of the large 4-engined spray aircraft.

Jack Barry. - USDA Forest Service. He has worked for many years on research programs aimed at furthering our knowledge of spray cloud movement and deposition.

David Smith. - Agricultural and Biological Engineering Department, Mississippi State. His specialty is in the area of droplet deposition on leaf surfaces and development of formulations and application technique to improve deposition.

Paul Fast. - Forest Pest Management Institute Canadian Forest Service. His research interests have been aimed at furthering our understanding of the mode of action of Bacillus thuringiensis (Bt) and developing strategies and techniques to improve its efficacy.

Chester Himel. - University of Georgia, Athens. He has been involved in spray physics for a number of years, and today will discuss his research with Bacillus thuringiensis.

William Yendol. - Pennsylvania State University. He will bring to us his current experience in the field of aerial spray applications and will highlight some of the problems and some difficulties with aerial spray applications.

I would like to take the opportunity to welcome our speakers and the audience to this discussion session. There will be opportunities for questions from the floor and we hope that with your active participation we will have an interesting and beneficial discussion. Additionally, it is desired that these discussions on formulation and spray technology will create further research interaction and more clearly focus on those mutually important problems.

SPRUCE BUDWORM SPRAY PROGRAM IN ONTARIO

B. H. McGauley, Pest Control Section, Ontario Ministry of Natural Resources, Ontario, Canada.

Today I would like to explain why Ontario has a smaller budworm program than the provinces and states to the east.

To explain Ontario's approach, I will outline the current spruce budworm policy. For the benefit of the American audience, I would point out that the Canadian provinces have the responsibility of managing the natural resources while the federal government's mandate is to undertake forestry research. Therefore, the policy that I am about to outline has been established at the provincial level and applies specifically to Ontario. The policy allows for three control objectives: epicenter suppression, to eliminate small defined insect epidemics; outbreak control, to contain larger infestations; and protection spraying, to protect the current year's growth.

In 1983, the spruce budworm infestation in Ontario spread across some 9 million hectares and the gypsy moth covered some 40,000 hectares. Therefore, the objectives of epicenter suppression and outbreak control were judged impractical and all spraying planned for 1984 is for protection. There are two categories of protection spraying: high value forests including provincial parks, plantations, seed orchards, seed production areas, wildlife habitat; commercially operable forests, i.e., those scheduled for liquidation within a five year period. The high value forests are usually identified by the provincial forest managers while the commercially operable forests are identified by provincial forest managers in consultation with industry foresters.

There are several constraints imposed on commercial forest protection spraying. The company must commit to harvest the forest within a five-year period, to initiate accessing the area within the year that spraying begins and complete road construction within three years. Protection spraying will be undertaken only three times in the five-year period. There are

¹J. A. Armstrong, A/Program Manager, Protection Canadian Forestry Service, Environment Canada.

²W. G. Yendol, Professor of Entomology, Pesticide Research Laboratory, Entomology Dept., Pennsylvania State University.

other constraints, but those which I have identified here are the most important. These constraints help to ensure that short term protection spraying is combined with targeted and accelerated harvesting. The goal is to prevent the establishment of large areas of balsam fir, but at the same time ensure that the forest users have sufficient wood to maintain a viable industry.

SPRUCE BUDWORM SPRAY PROGRAM IN QUEBEC

Michel Pelletier, Quebec Ministry of Energy and Resources, 175 St. Jean, Quebec, Canada.

For this presentation I will give a general picture of our experiences with Bt in Quebec since 1974. We started in 1974, applying Bt using DC-6B and CL215 as spray aircraft. The tank mix was Thuricide 16B® plus sorbitol in a 50:50 preparation. There was no calibration of the aircraft as we would now use the word, rather we just checked the aircraft for flow rate and sent it off on its spray mission. Although the Bt sorbitol mix was a good non-volatile preparation, after pumping a few gallons the meter jammed. We had no idea exactly how much was added since we had to estimate visually. The spray nozzles were the standard spraying systems nozzle with the tip removed; this gave an open nozzle with a 3/8" orifice. Even this large orifice became plugged with the spray mix. In spite of these problems, we had sufficient success to encourage us to plan a large program for 1975.

Prior to the 1975 spray season, spray calibration trials were carried out at Barstow, California, with the assistance of A. P. Randall and staff of the Forest Pest Management Institute. The formulation finally selected was Bt:Sorbitol:water in the ratio 50:20:30. During the spray season we did more experiments; in fact 11 combinations to assess differing mixes, swath intervals, etc. We had no success at all. We realize now that we didn't have a consistent droplet spectrum to rely on or even knowledge of the required drop size to give good results. This experience so discouraged us that for 2 years no trials with Bt were carried out. In 1976 and 1977, Dr. Smirnoff of the Laurentian Forest Research Centre was encouraged to participate and, although we don't know why, we had good results. Further tests were carried out in 1978. We realize that the major problem was aircraft calibration. At that time we really didn't know the best droplet spectrum, the desired deposit in terms of drops per unit area (degree of coverage), the volume per hectare required and the concentration of Bt required. We quickly determined that at an emission rate of 10 l/ha a treatment of 40 BIU/ha resulted in success. The mean deposit of Bt (measured in

petri dishes) was 77 colonies/cm² (ranging from 31 to 122); budworm mortality was 97.6% compared to 63% in the untreated areas, and defoliation was only 30% compared to 73% in untreated check blocks.

This success encouraged us to continue, and in 1979 11,000 ha were treated using Dipel 88® (Dipel 4L®), Novabac® and Thuricide 32B®. The emission rate was reduced to 7.5 l/ha, but with the same dilution and the treatment was 30 BIU/ha. Dipel 88 was mixed with water to give a 40:60 mix ratio. When the open nozzles were used with 154 Tyre nozzles, a swath width of 150 m was obtained. Droplets were collected on Kromekote® cards, petri-dishes and Millipore filters. With Dipel 88-97% of the droplets collected on Kromekote paper were 0-75 microns and 5% over 150 microns. These assessments indicate that the sprays can be classified as being made up of small droplets. This nozzle arrangement has been maintained except with FUTURA®, where only 110 nozzles were used. With improvements we now have a 300 m swath. Calibrations were also done in 1983, and in 1984 we will be using from 1.6 to 2.5 l/ha. Thus, since our start in 1974 when we used 10 l/ha, we are now down to 2.5 l/ha. We still have the basic question - are we in the right range of emission? We don't know if the droplets we are producing are the correct size, if we are losing a lot of small droplets, or if some are too large. To be able to do a proper aircraft calibration, we must know the optimum drop size to kill a budworm and the optimum size of deposition. Without this knowledge our tests to compare different products are meaningless; we will not know why one product is doing a better job than another. As I see it, the most important thing we must do is to determine the best droplet size to kill the budworm and the best to ensure good foliar deposit.

AERIAL APPLICATION OF BACILLUS THURINGIENSIS IN THE WESTERN U.S.

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The following summarizes my remarks relating to aerial application of Bacillus thuringiensis (Bt).

Quality of Application. No pesticide has ever been better than its application. Quality of application is dependent upon a correct prescription for treatment and proper execution of the prescription. Once the entomologist specifies what is needed on the target foliage for the biological effect, the spray strategist can write a prescription for delivering the proper number and size of drops to the target. But I

emphasize, that the spray strategist must be told what is needed at the target. For the application to be successful, however, the applicator must be capable and willing to execute the prescription details, otherwise Bt, in all likelihood, will not be effective. The majority of aerial applicators are professional. Unfortunately, they may not be aware of new application technology, nor how to use it effectively.

Properly calibrated and clean application equipment are other important considerations. Calibration becomes more critical as the application rates decrease below one gallon per acre. Calibration includes checking to insure that the spray system has the correct number and size of nozzles for the desired flow rate, and that the system is clean. Calibration is basic and we shouldn't have to worry about these matters -- that's why we hire a professional. But we do worry and for good reason. We can do all the proper things and then the link breaks down with the applicator. I estimate that 75% of the pilots and even company operators don't know how to calibrate properly. Does this come as a surprise to you? It did to me. Fortunately, the epidemic of poor application is subsiding.

Technical Representative. Because technical representatives have a vested interest in their product, no one is more interested than the technical representative in seeing the product meet its expectations and the control project meet its goals. The technical representative has a responsibility of being well informed on product mixing, tank mix, stability, atomization, degradation, adjuvants, application, etc. The Project Officer should utilize this valuable source of information.

Tank Mixes. Tank mixes have been changing rapidly in the formulation, amounts applied per acre, and degree of dilution. We are now applying less than one gallon per acre and we are beginning to apply the formulation undiluted. Paul Fast, FPMI, has calculated the amount of toxin required for an LD₅₀ for spruce budworm. Bt drops diluted more than 50% simply do not have enough potency to be effective. This insight has been a major breakthrough in understanding how to use Bt effectively. He further calculated that approximately two drops would be required per Douglas-fir needle. After aerial treatments of Bt tank mixes, applied at 96 to 128 oz/A, we observe approximately two Bt drops per spruce and fir needle. These two drops must contain sufficient toxin to provide a lethal dose to feeding budworm, and the lethal dose must be consumed before the effectiveness of the drops is lost through normal degradation.

The role and need for adjuvants in Bt tank mixes is not understood. We should be cautious in using an adjuvant until we understand its role regarding rainfastness, UV protection and

impingement -- and until we know how to handle the adjuvant in the field.

Determining the Success of Bt Treatments. In the past Bt has been used and its effectiveness evaluated as if it were a chemical insecticide. Chemicals usually show results within a few days. This is not the case with Bt. Entomologists in the West and East have observed dramatic results with Bt in reducing egg masses, larval population, and defoliation the year following treatment. Unfortunately we seldom look at second year results. I submit that frequently those supposedly poor Bt treatments were indeed successful; we simply did not know how to measure our successes. There are other problems -- land managers do not know how to plan the use of an insecticide that gives benefits the year following treatment, and land managers in the West have little confidence in Bt.

Meteorology. Results of studies by Canadian and U.S. scientists in recent years have uncovered the mysteries of how atmospheric conditions influence spray deposit, spray drift, and drop impaction on target foliage. Spray meteorology is, however, a complicated process and cannot be treated adequately in this discussion. Prescribing the meteorological conditions for a particular treatment must consider the tank mix, application rate, spray release height, topography, forest characteristics (species, density, canopy and height), and drift. Reducing drift often is the overwhelming consideration, sometimes to the detriment of a successful project. As an example, if drift is acceptable we can use small drops to provide good coverage and wind energy to impact the drops on foliage. Results of field studies, wind tunnel tests, and modeling have provided information and an understanding of how meteorology relates to effective treatments. Significant advancements made in this area over the past 5 years allow us to prescribe meteorological conditions leading to successful applications.

Modeling Spray Behavior. The USDA Forest Service has two models that predict spray behavior. These models can be used effectively as a tool in planning spray operations. They can be used to select type and position of nozzle on spray booms, decide on release height, select meteorological conditions, and select the approximate tank mix and atomization. The models predict deposit on the canopy, on the forest floor, and off target. We need to adapt these models to predict the probability of achieving deposition under various atmospheric conditions and forest types. We need the capability to predict, for the land manager, the probability of project success so he can evaluate cost/benefits. The land manager makes the decision, we provide the information for the decision.

Spray Deposition. Studies have demonstrated that conifers are excellent scavengers of spray drops and that the majority of drops are collected by the upper crown. The smaller the drop the greater the chance that the drop will penetrate the canopy and deposit on the ground. The smaller particles (<20 μ m) may enter, but eventually be ventilated out the canopy. Studies of spray deposition on the open ground vs on the forest floor show a higher percentage of large drops in the open (there was no vegetation for interception) and a higher percentage of small drops in the forest. On the other hand the majority of drops observed on foliage are less than 40 μ m in diameter.

Examining foliage is an excellent way to evaluate the adequacy of spray coverage. Spray deposit papers should be used as a qualitative sampler to monitor quality of application and drift. Deposit papers are inexpensive and simple to handle. When a better method is developed (easier and less costly), this information will be made available.

Wind Tunnel Tests. Prior to the availability of lasers, wind tunnels were limited as a method to obtain information on nozzle atomization. Wind tunnels with particle measuring lasers can be highly effective in providing quantitative data on drop size. The wind tunnel provides a means of identifying the effects of nozzle type and orientation, boom pressure, air-speed, and tank mix on atomization. Information from wind tunnel tests is used for input to models that predict spray behavior and for developing spray prescriptions.

SOME IMPORTANT FACTORS TO BE CONSIDERED IN SPRAY TECHNOLOGY ASSESSMENT

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Dosage mortality curves can be used in the field. By plotting the amount of mortality over deposit, an LD value can be obtained. If the degradation rate of the microbial product is also obtained, the established LD value can then be adjusted upward to compensate for this factor and, of course, this dosage level would be closer to the manufacturer's recommended dose.

There are dosage requirement differences between crop species. For example, to exemplify this, if we look at an adjuvant (this is a gustatory or feeding adjuvant on a soybean crop with Bacillus thuringiensis and Trichoplusia ni), we obtain about 78% mortality; on cotton 12.5% mortality; and cabbage 20.4% mortality. These relative mortality numbers change as you select different microbial-insect combinations

on these same crops. For example, good dose-mortality response has been obtained with a cottonseed meal bait suspension applied on soybeans. On the other hand, PVA-carbon gave poor results. The point to be made is when the LD values are adjusted for degradation, formulation, crop, etc., we always fall short of the manufacturer's recommended dose. Thus, there appears to be a research gap that needs to be filled and this would be either in the application-formulation arena or the biological response of the pests.

There is need for some type of standard in many of our application trials. In the literature, one researcher will use one type of test at this location, while others will do different types of tests with entirely different equipment, different materials, etc. Thus, a poor basis of comparison results. Usually even the evaluation methodologies are different.

In the applications area, a number of different types of application studies have been conducted throughout the country. In considering the over-the-top type application, drift spraying has been done using droplets in the 30-50 micron range; with and without electrostatic charges; with oil, water, and also with oil/water mixtures. We have also tried to inject the material into the side of the soybean canopies because these materials are highly solar-sensitive.

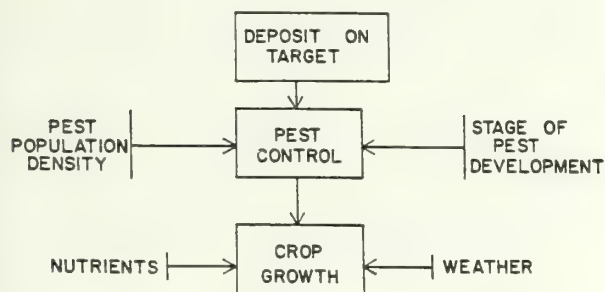
Vertical wedging in soybeans has also been tried. This technique forces leaves to the side so as to spray behind the wedge. We have also tried forcing the leaves vertically so as to spray in between the leaves as they are separating, again trying to penetrate the inner canopy.

The most promising technique is to simply bend the outer part of the canopy over and spray these areas as they are flipping back to an upright position. This increases canopy deposition about 20%. Probably the conventional over-the-top application for ground application is good as anything we have now.

Deposit Variation. The literature indicates that both across-the-swath variations and down-the-row variations, with most of your ground applications, will have a coefficient of variation (CV) ranging from 20-25%, specifically with broadcast applications, on smooth surfaces, and not plant surfaces. When using the crop, the across-the-swath variations with ground applications results in CV's up to the 35% range. In aerial applications with forest canopies, many of these produce 35-50% CV values.

A coefficient of variation of 40% translates into a maximum deposit which is about 3.5 times greater than the minimum deposit within the same swath. There are also problems from an application perspective in getting the material into the inner canopy parts.

With reference to the following table:



We are primarily interested in crop growth with the inputs weather and nutrients being very important. Of course we are also interested in pest control and there are many variables which affect it. Let's first discuss the area of deposit on the target and, specifically, formulation.

OPERATIONAL VARIABLES

METEOROLOGICAL VARIABLES

CROP FOLIAGE STRUCTURE

DEPOSITED:

1. DROP SIZE DISTRIBUTION
2. PESTICIDE CONCENTRATION DISTRIBUTION
3. DOSAGES
4. DEPOSIT DENSITIES

PHYSICAL PROPERTIES

DEPOSIT ON TARGET

PEST CONTROL

FORMULATION

1. SOLAR PROTECTION
2. REPELLENCY
3. ATTRACTANCY
4. GUSTATORY STIMULATION

First, consider formulation in terms of physical quantities; viscosity, density and surface tension. These properties can affect the droplet size distribution. Physical properties of the formulation can also affect its evaporation rate, and thus the amount of material deposited. Such properties as solar protection, repellency, attractancy, and gustatory stimulation may not affect the deposit on the target, but can affect the level of pest control.

The operational variables (such as pressure, nozzle size, nozzle type, flight height, flight speed, nozzle orientation) can affect the amount of on-target deposit. Meteorological variables (wind direction, wind speed, rainfall, temperature, humidity) also certainly have an effect. For a given crop, pesticide, pest and tank-mix formulation, there are four variables which can affect pest control (i.e., on-target droplet sizes, technical deposit, deposit density [no. drops/area] and tank-mix concentration).

Now let's consider aerial forest spraying at release heights of 50-200 feet above the crop. Drop size distribution, formulation and tank-mix concentration are generally reasonable well known.

Now, what do we know about these descending droplets that are volatile and evaporating, when they reach the canopy?

LOCATION	VARIABLES	KNOWLEDGE ABOUT VARIABLES
AT RELEASE HEIGHT:	1. DROP SIZE DISTRIBUTION 2. TANK MIX CONCENTRATION 3. DOSE	GOOD VERY GOOD VERY GOOD
AT TOP OF CROP:	1. DROP SIZE DISTRIBUTION 2. PESTICIDE CONCENTRATION DISTRIBUTION 3. POTENTIAL DOSAGE 4. POTENTIAL DEPOSIT DENSITY	? ? ? ?
DEPOSIT ON CROP:	1. DROP SIZE DISTRIBUTION 2. PESTICIDE CONCENTRATION DISTRIBUTION 3. ACTUAL DOSAGES 4. ACTUAL DEPOSIT DENSITIES	REASONABLE ? LIMITED REASONABLE
	PEST CONTROL	VARIABLE

Drop size distribution, very little; pesticide concentration inside the droplets, basically nothing (they have been evaporating) and we don't know the concentration or the potential dosage. For example, if we take an imaginary cube right above a tree, we do not know how to estimate the potential dosage. Potential deposit density (how many drops are in a cube above this tree) is also unknown. We know what left the aircraft, but the amount reaching a plane just above the target site is unknown.

There is some information available regarding deposited droplet size distributions and deposit densities. However, information about deposited pesticide concentrations and dosages is either severely limited or non-existent. Our research on row crops indicates that all 4, on-target variables are related to pest control. So when we have worked our way through these application problems, we eventually end up at our primary objective and that being pest control.

MEASUREMENT OF FOLIAR DEPOSITS OF BT AND THEIR RELATION TO EFFICACY

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Introduction

Interest in and discussion of the relationship between droplet spectrum emitted and droplet spectrum deposited, spray cloud behaviour, the relationship between droplets deposited and efficacy, and optimum droplet size, has increased in recent years and has resulted in a number of collaborative studies addressing aspects of these questions. The questions are particularly pertinent to operational use of *Bacillus thuringiensis* (Bt) preparations because Bt must be ingested, probably repeatedly, (Fast and Reginiere, Can. Ent. 116: 123-130; 1984) before it can act. Therefore, numbers of droplets deposited, their distribution on foliage, the probability of a larva encountering them, and the dose in a given droplet are important to efficacy. These considerations are as equally important to optimization of applications of contact insecticides, but they do not seem to have been adequately explored. The studies of spray cloud behaviour and deposition by the New Brunswick Spray Efficacy Research Group have established the optimum droplet size for deposition on coniferous foliage, as well as many of the parameters governing spray deposition. Fast and A. Sundaram, have begun the exploration of the effects of drop size, drop density (drops/needle or /cm. sq.) and Bt concentration on the efficacy of BT in laboratory bioassays on foliage. Here we present a narrative summary of the results of a field trial designed to measure the relationship of the number and spectrum of droplets deposited on balsam and spruce foliage in field applications to the emitted droplet spectrum and to the efficacy of BT. Space limits this discussion to a broad brush description of the experiment and the conclusions reached. A detailed description is in preparation. The experiment was jointly funded by Canadian Forestry Service, Forest Protection Limited, and USDA-Forest Service (CANUSA).

Formulation and Application

The Bt formulation chosen was Novabac 3 (32 BIU/gal) diluted to 6.3 BIU/L and applied at the rate of 30 BIU/ha. Tracer dye Erio Acid Red XB 400 was added at 0.2% w/w, and a sticker, Rhoplex AC33NP (Rohm and Haas) was added at the

rate of 2.0%. Studies by W. MacLean, USDA - Aphs, have shown this sticker to be much superior to Chevron sticker.

Laboratory bioassays established that neither the dye nor the sticker affected the toxicity of the Novobac 3.

Evidence from studies carried out in New Brunswick, Cranfield, and in the United States, show overwhelmingly that efficient impaction of drops and coverage of conifer foliage with ultra low volume applications can be achieved only with droplet sizes well below one hundred microns. Steps were taken to ensure maximum delivery in the range 30-50 μ after evaporation. Wind tunnel tests performed by the International Centre for the Application of Pesticides (ICAP) in Cranfield, Great Britain, established optimum settings for the AU 3000 Micronair atomizers to maximize the number of evaporated droplets in the < 85 μ range. A test spray run prior to spraying the blocks confirmed that 71% of all droplets found on needles were in the 25-75 μ range. Application was made by Cessna 188 flying swaths of 110 feet.

Two plots were sprayed. The first on 27 May, was treated when the balsam shoot development index was 3.8 and the larval index was 3.9 (indices as described by Dorais and Kettela 1982). Rain began within 4 hours of spraying and continued for the next 4 days, so no useful efficacy data was obtained but deposit measurement and foliar bioassays were performed. The second spray was applied 8 June when the balsam shoot index was 5.0 (open shoots) and the larval index was 4.8. Weather following this spray was sunny and warm. While spray weather was grossly the same in both sprays smoke from smoke bombs operated at canopy level showed the air to be much more turbulent during the second spray.

Atomization

Comparison of the volume fractions deposited on needles with the evaporated or target volume fractions reported in the ICAP study, shows that significantly more large drops were emitted than were found on foliage. Since the VMD was 85 μ , the 4% of droplets that were larger than 85 μ contained 50% of the Bt emitted. As drop size increases, this ratio becomes even more disadvantageous.

The effectiveness of Bt deposits on foliage is also directly related to the probability of an individual larva encountering and consuming a droplet, so deposit frequency is obviously a determining factor in efficacy. In the present case, the probability of encounter is approximately ten-fold higher for 30-85 μ drops than for drops over 85 μ in diameter.

Deposit

More droplets were deposited on fir needles than on spruce needles in both sprays, which may

reflect the inherently higher unit foliation of the spruce twigs (i.e. more and smaller needles). On the same species mean deposits were similar for the two sprays, 0.88 and 0.79 drops/needle on fir, 0.54 and 0.37 drops/needle on spruce. The median needle deposits were much lower, about 0.45 drops/needle.

Deposits on balsam fir buds differed significantly between the first and second sprays (0.55 drops/bud and 2.8 drops/bud respectively), but on the basis of drops/cm² of bud, they were not significantly different, 6.0 and 6.9 drops/cm² of bud respectively.

Deposits on Kromekote cards did not correlate with or reflect foliar deposits, averaging 21.1/cm² in Plot 1 and 6.2/cm² in Plot 2.

Spectrum

Droplet spectra on needles of both balsam and spruce in both sprays were very similar with an average of 75% of all deposits falling in the 25-75 u range. The buds, which were expected to be somewhat inferior collectors of small droplets, in fact collected more in the 0-25 u range (20%) than the needles which averaged 6% in this range. At the present time deposit levels in the 0-25 u range are probably not important due to the low amount of bt carried in these drops; however, future highly concentrated formulations might change the toxicological significance of these size droplets.

Spectra deposited on Kromekote cards were significantly different from foliar spectra with greater numbers in the high diameter range reflecting the now well established differences in impaction efficiency between conifer foliage and large flat surfaces.

The Rhoplex AC33NP sticker appeared to give excellent adhesion in both dry and wet conditions. While no quantitative data on sticker performance were obtained, it was found that individual droplets on foliage were stable to manual handling and remained apparently intact even after prolonged exposure to rain. The dye was seen to wash out of the deposits which, however, remained intact. One question which remains is whether the spores and crystals were contained within the visible deposits or whether they tended to wash out like the dye.

Foliar bioassays

Foliage was collected from nine sites, and five terminal shoots from each site were bioassayed with 10 lab-reared newly-moulted vth instar budworm to give 50 larvae/site. The bioassay was identical with that used for lab-sprayed foliage.

In the first spray, when the buds were still closed, there was no correlation between deposit and mortality. It was observed that larvae fed mainly inside the bud. This coupled

with the low deposit (0.55 drops/bud) resulted in the lack of correlation. In the second spray a good correlation between mortality and deposit was observed. When the data were transformed and plotted as probit mortality and log₁₀ drops/needle, a good regression was obtained with an R² of 81.5%. The 20% unexplained variation is probably due to within branch variation in deposit and the difference in deposition on old foliage, where the deposit was determined, and the new foliage where the larvae fed.

The LD₅₀ (determined by bioassay) of 6.3 BIU/L Novobac applied at 4.7 L/ha having a droplet distribution with an NMD of 23 u then is just over 1 drop/needle. The median deposit experienced at the nine sites in this part of the study was 0.4 drops/needle. These bioassays clearly demonstrate the dependence of mortality in field applications on the foliar deposit, in terms of both drop size and drop density at a given concentration.

Field Evaluation of Efficacy

Observed survival and defoliation were corrected for expected effects based on prespray larval densities. Survival and defoliation in controls were separately plotted against prespray larval densities on the same sample trees, regressions derived, and the regression used to correct observed defoliation and survival on a sample by sample basis in the sprayed blocks. The corrected effects were then plotted against drops/needle. A clear relationship between drops/needle and both survival and defoliation was observed. Survival was noticeably decreased at 0.5 drops/needle and at the 6.3 BIU/L concentration the field LD₅₀ was about 1.0 drop/needle which is in good agreement with the foliar assay and predictions from laboratory studies. Foliage protection (expected minus observed defoliation) also showed a relationship to drops/needle although, because of the low deposits observed (56% of samples had deposits of 0.5 drops/needle), the relationship was less clear than for survival.

No correlation was observed between deposit and total biomass/45 cm branch, biomass of buds/branch, or average pupal weight, because of extreme variation.

Several blocks in the same areas were sprayed under similar conditions with Bt at 12.8 and 14.0 BIU/L (Dipel 176 and Biochem Futura) again applied at the rate of 30 BIU/ha, but deposit was not monitored. These blocks gave significantly better control than the 6.3 BIU/L application used in the main experiment. Because the likelihood that budworm will encounter a droplet is low at the deposits measured on most branches, a higher concentration of Bt in those droplets will be expected to give more efficacious results. This hypothesis is to be tested in 1984 by relating deposit to field survival and defoliation at 32 BIU/gal, 48 BIU/gal and 64 BIU/gal concentrations.

No efficacy/deposit relationships were obtained on spruce in large part because the expected defoliation based on prespray larval counts was not observed.

STABILIZATION AND APPLICATION OF BT

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Introduction

This research report is concerned with: 1). A field application program using encapsulated Bt. The objectives of that program involved spray physics and the delineation of the critical parameters inherent in the delivery of Bt sprays to the microhabitat of the spruce budworm. The field application work was carried out jointly with Dr. Alam Sundaram and the Forest Pest Management Institute (Canada). Most of the data from the field studies will be published in a separate paper with Dr. Sundaram. 2). A laboratory program concerned with stabilization studies on pure Bt and BtI crystals. The laboratory studies on pure Bt and BtI crystals were carried out at the University of Georgia with the objective of providing a base-line system by which environmental parameters adverse to Bt (BtI) could be determined, quantified and controlled.

The application of pesticide sprays in forestry and agriculture, appears to be a simple procedure. It is widely assumed that each of the spray droplets in a spray cloud falls by gravity, over a time period determined by its mass (size), and that the downwind travel of droplets is directly related to that size (i.e., drift is directly related to droplet size). The final assumption of such simplistic concepts of pesticide sprays is that droplets can (fall) into the foliage system and kill target pests in their microhabitats. None of the above assumptions are correct, nor have any experimental proof. They are widely accepted. That wide-spread acceptance has had a devastating effect on pest management and ecosystem accountability. It is the single most significant cause of the present problems that beset the pest management industry. It provides no basis for survival of the industry into the 21st Century. Major changes, critical to the pest management industry may depend on the emerging science of pesticide spray physics.

The spray application of Bt has used the conventional wisdom of chemical insecticide application. Bt is a particulate toxin, has no contact activity, and requires substantially different spray methodology from chemical systems. The successful use of Bt in pest management requires delivery of a toxic dose to the target insect in a highly specific manner. That toxic dose must be injected by the insect within a limited time frame. That time frame is determined by feeding habits of the insect and by the stability (effective presence) of Bt on

the foliage within the microhabitat of the target insect. The mechanism of action of Bt, and particularly the effects of sub-lethal doses of Bt, requires that the "window of opportunity" with Bt be substantially greater than that required of most chemical insecticides. Optimum systems may require that Bt remain stable on the foliage for several weeks. Toxic levels of Bt must be provided on foliage ingested during a limited feeding cycle. Substantial residual action of Bt on foliage is important.

There is no general agreement as to the relative stability of Bt (as crystals) or Bt (as spores) on foliage, in the presence of UV light, foliage bactericides, and foliage pH. The second phase of the research reported herein was concerned with the stability of purified Bt and BtI crystals and the development of formulations to stabilize these biological insecticides. Purified Bt crystals were used to provide a base-line system for the study. Purified BtI crystals were used in the study because of the speed and simplicity of its bioassay.

Experimental Data and Conclusions

In 1981, the physics of spray delivery to a spruce forest were studied in a 15-hectare plot near Searchmont, Ontario. In 1982, two 50-hectare plots near Marathon, Ontario were studied. The 1981 research involved the use of encapsulated droplets of vegetable oil as a tracer system. The 1982 research was carried out by application of encapsulated droplets of Bt as a tracer system. During the 1981 test, wind velocity and turbulence was close to zero. In the 1981 test the wind velocity was 13-17 Km/hr. The combined data confirm that spray droplets larger than the range of 100 microns have substantially zero probability of delivery to the microhabitat of the spruce budworm. The delivery optimum (as a function of mass and number) is in the range of 15-50 microns. In general, typical Bt sprays used by present field application methods are not more than 5% efficient in delivery to the spruce budworm. To the extent that commercial Bt sprays are unstable on the foliage, the "window of opportunity" for spruce budworm control by Bt is very limited.

The data in Tables I and II, when combined with the physics of particulate distribution in sprays, and the feeding habits of spruce budworms, provide a basis for prediction that present field methods for spruce budworm control by Bt will continue to be marginal until brought into conformity with applicable physical principles. The quantitative analytical data available from the 1981 and 1982 research are not different from analytical data available from the fluorescent particle spray droplet tracer system (1969), the dry liquids tracer system (1978), the reversibly soluble pigment tracer system (1978), the fluorescent pigment system (1978-79), and by other research in spray

physics which has been published. In contrast, no quantitative data exist to support the widespread, widely accepted conventional wisdom that pesticide spray droplets of "any" size can fall into foliage, and can penetrate to target microhabitats.

TABLE 1
1982 SIZE RANGE AND DROPLET VOLUME
DISTRIBUTION: FOLIAR DATA

Drop size range (um)	Average drop size (um)	Frequency distribution %	Cumulative frequency distribution %
2 - 5	3.5	0.00	0.00
6 - 10	8.0	0.33	0.33
11 - 20	15.5	7.81	8.14
21 - 30	25.5	23.51	31.65
31 - 40	35.5	24.48	56.13
41 - 50	45.5	13.83	69.96
51 - 75	63.0	9.00	78.96
76 - 100	88.0	15.15	94.11
101 - 125	105.5	5.89	100.00

VMD = 38u

TABLE 2
1982 SIZE RANGE AND DROPLET
NUMBER DISTRIBUTION FOLIAR DATA

Drop size range (um)	Average drop size (um)	Frequency distribution %	Cumulative frequency distribution %
2 - 5	3.5	3.22	3.22
6 - 10	8.0	14.17	17.39
11 - 20	15.5	46.56	63.94
21 - 30	25.5	23.76	87.70
31 - 40	35.5	8.18	95.88
41 - 50	45.5	2.38	98.26
51 - 75	63.0	0.90	99.16
76 - 100	88.0	0.71	99.87
101 - 125	105.5	0.13	100.00

NMD = 13u
Dmax = 110u
Dmin = 3u

The stabilization and formulation studies were approached on the basis of use of purified crystal preparations. The crystals were isolated by renografin gradients, followed by suspension in deionized water. The fluorescence studies were made with crystals solubilized with dithiothreitol. Quartz cuvettes were used to allow study of the absorption and fluorescence emission of the solubilized preparations. In order to determine the effect of a standardized (hard) UV source, crystals were suspended in a quartz cuvette and irradiated for specific periods of time. Aliquots of the suspension were then solubilized and the fluorescence emission obtained. Other aliquots of the crystals were used to determine biological activity. The biological activity studies were limited to BtI because of the ease and speed of the bioassay procedure. At present we are starting bioassay work with cabbage looper (*T. ni*), and with cotton boll worm (*H. zea*). The fluorescence data obtained were not different with Bt (HD-2) crystals and BtI crystals. The fluorescence spectra correspond to protein tryptophan (class

B proteins) in which the tryptophan exists in a non-polar environment.

Under the experimental conditions used, BtI and Bt crystals are photolytically unstable and their tryptophan fluorescence decreases relative to the time of irradiation. In the case of BtI, that decrease in tryptophan fluorescence is directly related to decrease in biological activity. If tryptophan fluorescence can be correlated with biological activity, then it could be a basis for analytical quality control, by spectroscopy. The tryptophan absorption spectra show no significant differences before and after irradiation.

Encapsulated formulations of BtI crystals with UV-Chek® (Ferro Chemical Co.) were prepared and subjected to irradiation using the same UV source under standardized conditions. Under these conditions, unprotected BtI crystals lost all biological activity after 6 hours. At present we have found no loss in biological activity of encapsulated, protected, samples irradiated continuously over a period of 20 days. In control studies, all adjuvant components of the formulation were shown to have no adverse effect on the mosquito larvae.

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SPRAY SWATH PATTERNS OF SMALL AIRCRAFT AND VERTICAL DISTRIBUTION OF MICROBIAL SPRAY DEPOSITS

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Introduction

Each year in Northeastern United States over 500,000 acres of oak forests are aerially sprayed to prevent massive defoliation by the gypsy moth. In Pennsylvania alone 400,000 acres were proposed for treatment in 1983 with commercial preparation of *Bacillus thuringiensis* (Bt).

Preparations of Bt must be consumed by the pest insect to be effective, and cannot be absorbed through the insect's integument like most of the organic insecticides. Therefore, it is important that the Bt spray deposit be distributed evenly over the feeding surface and in sufficient quantity to be lethal. Consequently, the more efficient and precise the application

technique is, the greater chance that the target site will collect an amount that will be efficacious.

Aircraft calibration and lateral spray deposit distribution determinations are generally considered routine activities prior to aerial spray operations, but such results are usually omitted from the literature. Consequently, comparisons between different aircraft is difficult. In addition, the actual relationship between the spray droplet characteristics and their biological activity has virtually been unexplored with microbial pesticides, including those used against the gypsy moth.

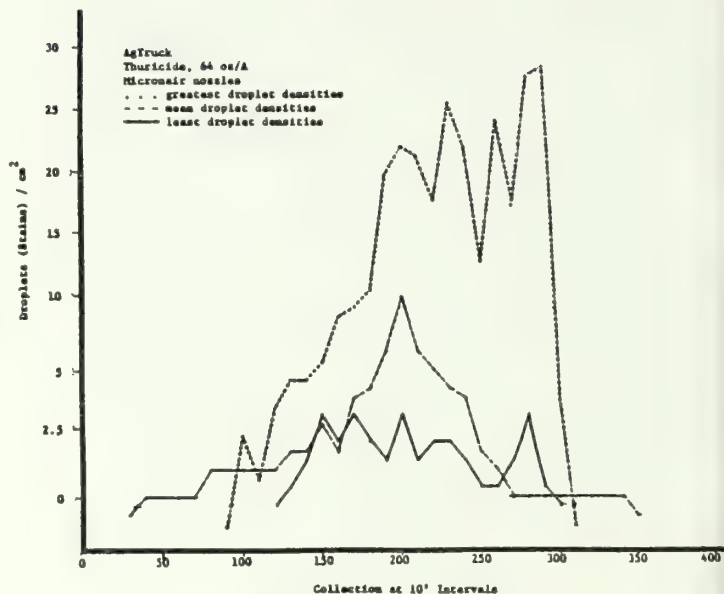
Swath Widths

The term, swath width, is generally defined as "the area (span) in which the amount of spray expressed in various ways equals or exceeds a specified amount thought to produce the requisite effectiveness." In these trials "lateral distribution width" (LDW) was used to mean the detectable spray that was deposited over a surface at various points along a 90° lateral direction on each side of a forward path of the application system.

In 1983 swath width trials were conducted using a Cessna AgTruck®. The aircraft's speed was 120 mph. The nozzle systems used in these trials were the Mini-Micronair (AU5000) and the flat fan, stainless steel No. 8004. Two commercial preparations of Bt, Thuricide 48LV® and Dipel 6L®, were used at the rate of 12 BIU. These formulations were applied at the rate of 64 fl. oz./A. The aircraft was calibrated for a 75' swath width and the spray applied at 40 PSI pressure. White 4 x 5" Kromekote® cards, placed on 2' wire stakes, were spaced at 10' intervals and used to collect the spray emission. The aircraft was then flown 50' over the collection line and into the wind. Most of the LDW applications were made in the early morning hours and when no wind could be detected.

The LDW resulting from the Bt formulations dispersed by the Micronair AU5000 nozzles ranged from 90 to 270 feet with a mean of 188 feet. In a few trials low force cross winds were present and did skew the droplet distribution slightly.

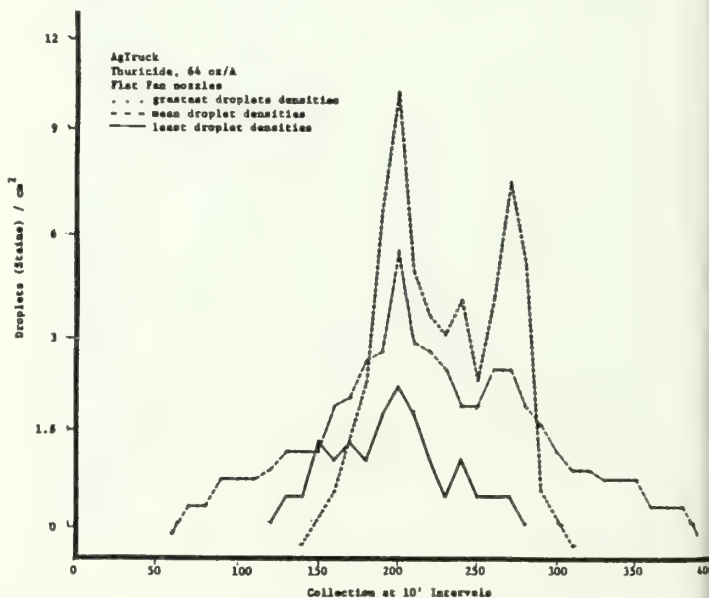
The following figure illustrates the droplet (stains) density spray patterns over the 400' detection line:



Three curves are presented, one showing the greatest droplet density, another the mean droplet density of 12 Micronair trials, and another the LDW curve depicting the trial having the least droplet densities.

The mean number of droplets/cm² for the total LDW of the various trials varied from 0.5 to 12.5 with an overall average of 3.5 droplets/cm². Peak droplet densities ranged from 28 to 3 droplets/cm². In the 24 trials, including Thuricide and Dipel, there was considerable variation in the LDW and/or swath width with regards to droplet density.

The following figure illustrates the droplet density (stains) spray patterns over the 400' detection line for the flat fan No. 8004 nozzles:



These spray droplet patterns show the greatest droplet densities/cm², the mean droplet density of the 12 flat fan trials and the LDW curve depicting the trial resulting in the least droplet densities.

The total LDW for Bt dispersed by the flat fan nozzles in a single flight pass ranged from 160 to 400 feet. For all flat fan trials the overall LDW mean was 255 feet. In general, meteorological conditions were stable, but wind speeds were detected in some trials ranging from 7 to 10₂ knots/hour. The mean number of droplets/cm² for the total LDW of the formulations ranged from 0.4 to 4.3 with an overall average of 1.8/cm². Some collection sites obtained droplet density means of 10 droplets/cm², while others were much lower.

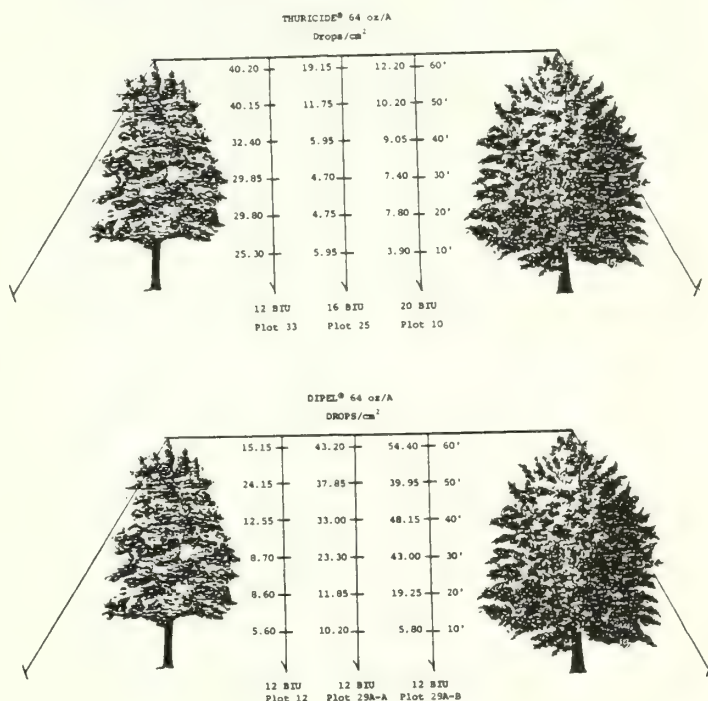
When the replicated trials or flight passes were compared considerable variation was found in droplet density and spray deposited in the LDW patterns. With such variation between trials, it would seem that an applicator would have a problem in selecting an LDW pattern that would more accurately characterize the aircraft type and be used in its calibration. Although some of the prescribed techniques for determining aircraft-spray swath widths or LDW are suitable, there remains the need to develop standard techniques that will provide a more accurate estimation of these parameters for each aircraft type. The following questions still remain unanswered: In calibrating an aircraft should it always be flown into the wind and only when such conditions prevail, or should the swath width determinations be undertaken in "0" wind conditions? What elevations should be used for the swath determinations? Should multiple flight paths be used in addition to a single flight path?

The overall average volume mean diameters (VMD) of the Micronair was 186 μ m for Thuricide and 165 μ m for Dipel. For the flat fan nozzles, the overall average VMD was 304 μ m for Thuricide and 262 μ m for Dipel.

Aerial Evaluations

To evaluate spray deposits at various elevations, a series of vertical lines were constructed and secured to a horizontal aerial line. The horizontal line was attached to the canopy tops of two oak trees. Using a cork-paper clip attachment system, collection surfaces could be positioned at various intervals along the upright aerial line, usually at 10' intervals. These aerals were placed in open spaces in oak forests being treated by air with Bt. With this system an evaluation of the physical droplet characteristics including VMD, density, and spray mass per unit area could be made.

The following figures illustrate the droplet densities that were collected at various heights in an oak forest being treated with Thuricide and Dipel at 64 fl. oz./A by air:



When spray droplets were collected at various elevations and their densities compared, the 60' elevation collected at least 3 times more droplets than the 10'. In the case of the Thuricide treatment, the VMD's ranged from 286 to 590 μ m. In most trials the bottom card had the largest VMD of 50 μ m. These preliminary investigations clearly indicated that additional research is needed to better understand droplet distribution in a free-fall system and within the oak canopy.

GENERAL DISCUSSION

D. SCHMIDT: Having listened to the previous speakers talk about the problems of pesticide application, I have a question. "Given the information available and not what you would like to have, and knowing the equipment that the operator has, can you give an estimate of just how effective his spray program will be?"

M. PELLETIER: I really can't answer that question at the operational level -- many times we just cross our fingers.

D. SCHMIDT: I understand your problem as an operator, but I thought that some of our other speakers who have talked about the information they have and what they would like to have would want to know if their operation was going to be a success.

W. SMIRNOFF: Just one comment, your explanation is valid if you study chemicals which are a solution, but with a suspension such as Bt it is not the same. The number of spores per droplet can vary from one to several hundred thousand.

P. FAST: On the contrary, we have laboratory data to show the exact number, or very close to the exact number, of spores and crystals in a droplet.

DISCUSSION PANEL: FIELD TEST DESIGN & DATA ANALYSIS

Panel Members: Daniel M. Schmitt, Chairman; William E. Waters; B. Leo Cadogan; Gerald S. Walton

Panel Chairman:

I think it is time to open the panel. On my left respectively are Bill Waters, Professor of Entomology and Forestry, University of California, Berkeley; Gerald S. Walton, Biometrician, Northeastern Forest Experiment Station, Hamden; and Leo Cadogan, Forest Pest Management Institute, Canadian Forestry Service, Sault Ste. Marie, Ontario. My name is Dan Schmitt, Program Manager, Northeastern Forest Experiment Station, U.S.F.S., Broomall, Pa.

I am going to ask each of the panelists to discuss field test design and data analysis for pesticide applications in the context of three general areas: (1) field and pilot tests, (2) current approaches to experimental tests, and (3) suggestions and possibilities for improving experimental tests. Bill?

Bill Waters:

There seems to be a general understanding as to the role of field testing, but not as to its purpose. The purpose should be to find the most efficient combination of treatment variables, i.e. formulation, concentration, application rate, atomization, and timing, that will consistently provide a specified degree of control of the target insect and/or foliage protection under operational conditions. The question is not which treatment or treatment combinations perform best, but which, if any, will achieve the desired results. Comparisons are of course part of the process of evaluation, but they are not the purpose of field testing itself.

In order to achieve the purpose of field testing we need to have performance criteria, which should be stated in advance. These criteria are the explicit bases for evaluation. The best way to state criteria is in terms of what remains following treatment, not in how much a population is reduced nor how much defoliation has been reduced. For the insect this means number of survivors, not percentage killed; for foliage, the amount remaining not the amount lost. If we are truly managing pests, we must to be able to make decisions on alternative treatments in terms of probable outcomes over a time span meaningful to the Forest Manager. The models that are being developed for this purpose therefore deal with insect survival densities and amounts of foliage produced over time with and without treatments.

Once we are clear about the purpose of field testing, we can consider the distinction between field experiments and pilot or operational tests. Both come under the umbrella of field testing.

Field experiments simply involve experimental combinations of the treatment variables applied under field conditions, with the understanding that the insect is present at measurable densities. Practically, this means a range of population levels causing sufficient defoliation to be considered for control. Field experiments also imply that the equipment employed (unless the manner in which it is employed is itself a treatment variable) is representative of conventional operations.

Everyone is eager to go from the laboratory to the field. However a basic rule is that field experiments should be initiated only when the treatment variables have been reduced to a number that can be reasonably encompassed in an efficient experimental design. Generally, these variables are best combined in factorial designs, but a relatively large number of units are required for even a simple complete experiment. For example, a single replication of a factorial experiment with two levels each of four variables requires 32 plots. In many cases, incomplete designs are necessary. To acquire all of the information needed a programmed sequence of experiments must be planned.

Pilot tests are operational field tests of the treatment found to be optimal by field experiments. The purpose is to determine how well the treatment performs under fully operational conditions. When field experiments fail to distinguish an optimum treatment, there may be justification in subjecting several to a pilot scale operation. In such cases, special care should be taken to acquire the information necessary for objective evaluation, with adequate data taken to assure that comparisons can be made in terms of specified performance criteria. One need only consider the tremendous cost of pilot scale tests to appreciate the importance of sound progression through all developmental steps to the pilot scale test, and the need for adequate data from the test itself.

Currently we seem to design, often simplistically, both field experiments and pilot tests and then compromise them because of 'realities'. I have had much experience with such negotiations and compromise and, in my opinion, they have in many cases killed us, i.e. time and again we have obtained inconclusive results. It behooves all of us to start with basic concepts, objectives, appropriate experimental designs, and adequate sampling, and stick to them.

A related problem affecting the current difficulties in interpreting the results of field tests with B.t. is differences in expectations regarding outcomes--expectations of what constitutes satisfactory performance with regard to suppression of the insect and foliage protection-- and, in fact, of opinion as to differences in expectation of which objective is the most important, or whether there is an optimal balance. If there is not agreement on

what we expect, how the devil can we design an experiment or pilot test to get specific information to evaluate performance? Because we don't have a clear understanding on what constitutes satisfactory performance nor when it is optimal to move from the laboratory to the field, we have a continued history of what I would call premature field experiments.

In listening to the previous speakers, I was struck by the fact that people essentially referring to the same range of data, were supplying quite different interpretations. Obviously, there can be little developmental progress if the same data mean different things to different people.

For the spruce budworm there is a scientific basis from population studies for specifying minimal performance or even better, what the outcome will be. There is a basis in spruce budworm research for saying whether 5% survival is or is not satisfactory, for example. Better, it is possible to state, given x number of insects on a 45 cm branch after a control operation, what the number is likely to be the next season. It is the neglect of population information, and unrealistic faith in efficacy couched in percent population reduction, percent foliage reduction, etc. that has caused public agencies to lose credibility and, in the case of the US Forest Service, to find itself in court. Managers simply do not understand, after being told that an operation on their land resulted in a certain percent population reduction or foliage protection classified as successful -- why, the following season they must spray again.

The only other comment I want to make on future improvement applies to sampling. Our basis for evaluating field tests is the data we gather. The small data sets usually planned for, and subsequent compromises, have left us with a very small data base on which to make evaluations. Our current procedures in this respect are not only scientifically unsound, but irresponsible in view of the terrible price we have paid in credibility. I will make one suggestion regarding population sampling. Since the objective is to determine whether or not the surviving population is at a level specified for a satisfactory control operation, sequential sampling is the most efficient procedure.

Chairman:

Thank you, Bill. Jerry?

Jerry Walton:

I think the main concern in a field experiment is that the objectives be very clear and well defined. Certainly it would not be useful to restrict research objectives nor should the same data on populations, foliation, etc. be collected for every objective. I see the field experiment

as a method of answering very specific questions and not as an occasion to collect miscellaneous information.

Nor do I believe that field experiments should be necessarily duplicate operations, e.g. with respect to gallonage and dosage. It may be the purpose of the experiment to establish an optimum, in which case it is efficient to determine the end points for the parameter in question. Whether or not these end points are realistic from an operational standpoint is irrelevant.

Once specific questions, i.e. objectives, have been formulated the place to start is with an adequate design. Constraints on time, space, and funding may make compromises unavoidable. But one must constantly ask if a compromise is really necessary. The availability of suitable test areas is often a problem-- a limiting problem. In such situations some adjustments in ideal design may be necessary. One possibility is to use smaller spray blocks. But if the blocks are too small, the results will not be transferable to operating conditions. So there has to be some happy medium. Knowing costs and other constraints, one can proceed toward the optimal design.

Having mentioned costs, it should be clearly understood that information costs money; you are going to pay for what you get. Also, if you don't get the information, you lose everything. But we often do things that are costly and do not provide useful information. For example, placing deposit collectors next to trees with the idea that the droplet record on the collector can be correlated, by tree, with population reduction or foliage saved. The difficulty here is that population mortality on a single tree is so largely unknown that you cannot establish a correlation that is practically significant. And yet a great deal has been spent on this sort of thing.

There is a tendency also to expand objectives, a feeling that collecting additional information for another objective is a more useful way to allocate resources than intensifying the sampling to collect data relevant to the specific objectives of the field experiment. The result is a waste of sampling effort. I think the Core test¹ is a prime example. You go out with very marginal sampling efforts and many sub-objectives on the assumption that things are going to go right -- and they never do. Any time anybody says, 'well, as long as we are out there we may as well measure ...', don't. It is a waste of time better spent on the collection of relevant data.

Conforming to conventional approaches to field experiments is another insidious means of wasting resources. For example, we tend to use the same post-spray sampling time sequence, irrespective of what insecticide, microbial or chemical, is used, or what species the target insect is. I think a lot of our problems stem from traditional

approaches with little thought to the problem and experimental conditions at hand.

There is another kind of mind set that affects data analyses and interpretation of field tests. I call it the DDT syndrome, the feeling that at least one of the treatments must produce results equivalent to what DDT would have. Saying it, or on paper, this is nonsense. We don't do research this way. But why then is there wide spread resistance to adjusting post-spray population data for natural mortality? It is also traditional to consider a field experiment a success if, using sophisticated statistical testing methods, you can detect whether or not you sprayed anything. That is all "statistical significance" means, and it is hardly a worthy criterion for success.

Do we need to measure foliage protection? I don't think that is the way to ask the question. Better, given the objectives of the experiment, does foliage protection tell us anything? If, for example, the size of the surviving population after treatment compared to pre-treatment size is the issue, foliage information is not relevant. If the rate of mortality is the issue (i.e. how soon the insects die), then the level of foliage protection is an indication of how effective the treatment was. In brief we should clearly think through the purpose of a field experiment, frame the questions to be answered specifically, design efficiently, and collect data, and enough data, to answer the questions, and collect no other data.

Before discussing improvements, I'd like to comment on performance as a general objective of field experiments. My general attitude towards a field test is that it is to derive information. It is my feeling that trying to reach goals that will make the user happy has interfered with doing just that. Interim specific objectives should be interposed as part of a planned program of testing leading to optimal performance, rather than performance as an objective per se.

Another point, which struck me especially at this meeting, is that operations people normally make incremental adjustments in spray and insecticide parameters to improve efficacy. They may well be ahead of research in appraising the effects of such changes, though without the analysis. So maybe the area in which research can help most would be evaluation of the radical and innovative things that people in the field can't justify.

¹Refers to a microbial field test reported in "Spruce budworm core B.t. test -- 1980: combined summary. USDA Forest Service RES. PA NE-506." The chairman of this panel suggested the general approach and imposed funding constraints. Experimental design and sampling methods were the product of an ad hoc committee.

I do not like the current use of controls -- check plots. There is something suspect about their selection, about the way control populations behave. Perhaps it would be better to establish a standard treatment as a basis for evaluating experimental ones.

Again, depending on the objectives, you may not need controls. If the objective is to compare two treatments, the control in the traditional concept does not provide relevant information. Finally, although new statistical methods and approaches to experimental design and data analysis are coming on line all the time, there is nothing in statistical theory per se that is going to make the entomologist particularly comfortable in his field experimental work.

Chairman:

Thank you Jerry. Leo.

Leo Cadagon:

There are misunderstandings about field tests, especially field tests involving the use of microbials. Microbials must satisfy biological or natural laws; however when encompassed as part of a spray, their application is governed by certain physical laws. Predicting the behavior of biological entities is very much more hazardous, because of their biological properties, than of abiotic entities which conform to chemistry and physics.

The Canadian Forestry Service has an experimental protocol intended to lead to the registration of the pesticide and all that that implies. The protocol starts in the laboratory. Laboratory investigations treat toxicology, LD-50 assays, half life of the material, formulation tests, analyses of stability, determination of physical and chemical parameters affecting delivery as a spray, etc. In general laboratory investigations are intended to identify problems at an early stage and resolve them. There is no reason, for example, to go to the field and find out 'it didn't stick'.

The next step is single tree application experiments. Here information is gathered on deposit characteristics, more information on stability under more realistic conditions. We then proceed to small scale trials. These are thorough experimental trials. The intention is not just to evaluate potency but to acquire information leading to improvements in the material or its application. We then proceed to semi-operational trials on about 300-400 hectares. These are often laid out or supervised by forest or forest pest managers but data collection and the rigor of analysis approximate the level of small scale field tests.

If all goes well we will have identified an insecticide, its appropriate formulation for the delivery systems which are likely to be used, and performance information over a range of probable conditions. We are now ready to conduct large plot operational trials.

I mentioned earlier that microbials, particularly B.t., have unique properties some of which are very desirable. Consequently there is a temptation to go into the field early to see how it works, bypassing much of the protocol described. If the product fails, one can argue that you should not have gone to the field. But a field season has been wasted and often field tests provide data which suggest that a single factor caused the failure and the manager can fix it. So the product does not go back to the laboratory; the manager "fixes" the problem and the product is field tested again the next year. In this way an error-prone, insensitive, cyclical adjustment process is introduced. In fact microbials are one of the few products where, years after registration, exploratory research that should probably have been conducted prior to registration is still being conducted.

Regarding current methodology I presume Dan (the chairman) was asking for opinions on the B.t. Core tests. Now, conducting research in a natural forest is a difficult task. Conducting research with microbials is doubly difficult. I presume the core tests were initiated to deal with inconsistencies. Although the concept (multi-location field tests, each with the same experimental design) is a good one, I am not sure it can deal with inconsistencies in microbials.

Classical agricultural designs cannot always be adapted to natural forests, although they may be suitable for plantation R&D. Designs for forest research must consider the many constraints that are evident in natural forests. One of the most restrictive for formulation and application R&D is the availability of adequate sites -- those with suitable insect populations, accessibility, and which are conducive to safe aircraft operations. The design must take into account logistical requirements, be realistic, and not carved in stone.

However the original design should still be optimal. If absolutely necessary, compromise! For example I do not think you can find enough areas in Ontario to conduct a truly randomized design involving more than two variables. Last, but not least, you have to recognize the "Chancellor of the Exchequer". We can always design the experiments we like, but the money might not be there.

Finally, after listening to the discussions of the past two days, I feel that perceived difficulties with products, formulations, and delivery systems, might be really design problems. It should be recognized that design includes specifications for implementation, including sampling. We need to honestly look at the procedures we employ in relation to design.

Regarding improvements in current methods, I think first of all we have to tackle attitude. Researchers in microbials are perceived to be promoting, not testing, microbials.

As mentioned there is room for improvement in design. Whatever the outcome of the core test¹, to the extent it was a cooperative effort, it was a start in the right direction. I think all the actors need to get together very early and settle design problems. Positive controls in the sense of a standard treatment are worth looking at, but they add expense. Actually I have no problem with check plots provided they are representative of the area and the population. Sampling is a problem, but it is one we can deal with.

Analyses and interpretation of microbial field tests are difficult. Anyone who has seen Ed Kettela's presentation ("Review of problems with efficacy of B.T.K. in spruce budworm control operations in the Maritime Provinces of Canada" in this Proceedings) will appreciate what I am talking about. For example if A, with 98% defoliation is significantly different than B, with 96%, practically what does this mean? Probably nothing. We have an obligation to carefully and objectively interpret data and not to take refuge behind a barricade of statistics and meaningless statements of "significance". Thank you.

Chairman:

Alright, we will now entertain questions and comments. Wladimir?

Dr. Wladimir Smirnoff. Dr. Waters commented that field tests should be representative of operational conditions. But if the product or formulation provided for experimentation is under or over strength interpretation of the results is going to be very very difficult.

I'd also like to comment on Leo's remarks on registration. Because a product is registered people spray big territories with it without paying much attention to the label and also there can be a problem of the type I just mentioned. Sometimes believing in the registration without regard to the label or professional research advice can lead to big mistakes.

People also don't appreciate true costs compared to out of pocket costs. For example in the name of economy some applicators prefer to increase the dosage, and volume rather than perform calibration tests, and so artificially increase the cost by 50%. Others try products which worked on 6th instar larvae which is ridiculous since defoliation is already completed.

I agree with Dr. Waters that we must have standard criteria for evaluating pesticide applications. Currently criteria fluctuate from operation to operation, and it is impossible to fairly evaluate performance.

Next, combining B.t. with some chemical is unacceptable since it has never been studied.

The dye Erioacid red, for example, has been added at the rate of two kilo/100 gal. regardless of the effect on the formulation. No further comment.

Chairman:

Thank you, Wladimir. I believe you were endorsing some of the panels' comments. I think the panel tangentially addressed the matter of information expected from field vs pilot tests. Does anyone from the audience care to comment. Jim Bean?

James Bean:

Listening to the discussion, I am sure Bill (Waters) went back to probably 1962 because he is saying some of the things he said then. And it is just as apropos today. There is a definite need to start at the beginning and get good basic information. I agree we have often gone to field tests too soon.

John Cunningham:

I never really thought of two particular categories of tests. Viruses are rather a peculiar type of biological insecticide and it is probably necessary to take them to the field at a fairly early stage to determine if you will get a virus epizootic. In other words you want to see if there is a cumulative effect.

You can get great results in the laboratory, but in the field there may be a success or a total failure. The forest includes a range of factors that cannot be evaluated in the laboratory. John Podgwaite may want to comment on this as he is working with Gypsy Moth virus. So I feel for potential virus candidates, the only thing to do is to take them out and try them in the field at a fairly early stage. The alternative is to use viruses as B.t. -- in which case they become fairly expensive stomach poisons. We really can't go this route with viruses.

Another factor, not mentioned so far, affecting field tests is the health of the target population. Now older populations of budworm become heavily infected with microsporidia. There is extremely little work done on the differences in population quality and how such differences affect insecticide applications, although Wladimir has done some research on this subject in relation to B.t.

I conducted some small laboratory tests and find high mortality following NPV infection, if the larvae are previously infected with microsporidia or B.t. On the negative side virus yield from such insects is very much reduced.

Another factor that crops up in the field is fungus epizootics. They may affect your check plots or treated plots. The only way to check this possibility is to examine your population samples microscopically in the laboratory.

Chairman:

Thank you John. You did raise an issue -- population quality -- that needs to be more thoroughly explored. And, of course, there is another, host quality. The panelists and the comments from the audience have stressed the inadequacy of information collected. And here I will raise a question. It is customary to collect information on current defoliation. In the case of microbials, in a research sense, is this the information we want? Anybody care to comment?

Paul Fast:

I will. If you plot some population measure, larvae per bud, or buds per larvae, against defoliation, you will get the following kind of relation (illustrates). The point is you can measure the variance about the regression or correlation and get a darn good idea of what effect your measured population is having on defoliation. We find that larvae/bud instead of larvae per branch provides a narrower variance.

Now once your experiment is finished you can plot the location of your test plot on the graph. You can then see by inspection whether it falls within the confidence limits of the graph and determine whether you got the desired effect.

This is more expensive because it means doing three or four or five checks at different population levels in order to get the curve, but it is much higher resolution than using one or two or several check plots to compare differences in a number of parameters between treated and check plots. In brief the resolution of the evaluation technique we currently use is not good enough to detect the kinds of differences we are interested in.

Chairman:

Thank you Paul. Wladimir, you wanted to add something?

Wladimir Smirnoff:

Yes. Based on my figures of foliage protection obtained over many years in permanent plots with careful measurement of larvae/bud, larvae/branch, dead larvae, new buds, etc. before and after treatment, I can say that it is possible to project foliage protection in terms of tons/hectare/year.

Chairman:

Thank you Wladimir. Now I'd like to add a thought regarding lab tests, field test, pilot tests. The idea, which has been roundly trashed everytime I mentioned it, was that the lab tests should provide all the information on toxicology, stability, resistance to water, etc. and the purpose of the field test then was to essentially

raise the question of why the field test did not come out like the laboratory test.

It sounds like a fairly ridiculous idea, but it occurred to me that if such a research protocol had been in place, the need for the kind of research that Charles Wiesner, Paul Fast, and others are doing now, would have become evident much, much sooner.

Dr. Waters:

I don't think that is a legitimate or relevant question. Admittedly, laboratory research is the foundation for the field experiments, but the questions to be raised and the hypotheses to be tested in the field experiments are of a different sort, having to do with operating characteristics of the material. The information base for the two kinds of research is not the same. The lab tests lead to the field tests, but one doesn't test the results of one against the other.

Chairman:

I won't pursue this matter any more, but will turn to a subject first mentioned by Dr. Waters -- the need for programmed experiments. He pointed out that experiments could be conducted over time. That is a missing ingredient in field testing -- a total design in which time is one of the variables and in which one set of factorials would be put in one year and the total experiment might require three years.

Imants Millers:

The problem is that, in B.t. in particular, the product changes faster than you conduct the research. For example of what value were the core¹ tests? Current products in use are completely different than the tested ones.

Oswald Morris:

I have heard a lot of rather wild statements this afternoon and so will make one of my own. First, I do not think there is any such thing as a failure or a negative result in research. Research is a continuum. Negative results are merely steps in a positive direction.

Carol S. Glenister:

I am a private contract researcher working with Gypsy Moth. People concentrate on evaluating levels of defoliation when they do not know what the volume of leaf tissue is in the field. Assume you have a population, one population, and it will consume 100 kg. of leaves. If the volume available is different in the plots -- and you don't know it -- the percent defoliation will be different. Add different treatments and different populations on the plots, it is easy to see that the current expression of the defoliation is meaningless.

Dr. Waters:

This is just one of the problems in expressing results in terms of defoliation. There are other problems with using defoliation as a measure of treatment effectiveness. The use of check plots for this purpose is particularly questionable. These problems can be avoided by getting sample counts of known precision and using them to relate to populations in treated plots.

Carol Glenister:

In the lab you have known mortalities and known population. In the field you essentially don't know mortalities and you think you can go from percent defoliation to residual population. But you can't unless you know what the volume is that is being consumed.

Now there are models available in which foliage weight can be estimated from tree diameter. You can still use visual percent defoliation estimates but you would have to convert it back to volume consumed in the stand. You can then better estimate what happened following treatment to your population and then compare percent mortality in the field with lab mortality.

John Cunningham:

One thing we need to remember in expressing results, like "foliage protected," is the client. In gypsy moth the client is usually the home owner; in budworm, the forest manager, etc. Each insect affects a different client, so you need to express results that are meaningful in the context of the client's problem.

Leo Cadogan:

Yes, but the researcher's clients also differ at the experimental stage and the field stage. In research I think our clients are our colleagues or peers, and it is very difficult to say to them, "it didn't work" or, "it was fairly good." That is fine for the homeowner, but not for persons who expect a more definitive statement of results.

Dan Kucera:

Getting back to the availability of virus suitable for field and pilot testing, cooperators who provide such areas are increasingly concerned about environmental impacts. I think in the future we are going to have to be very careful in telling the land manager what we plan to do, how we are going to do it, what we hope for in our results; and we must assure the land manager that we are going to take all the precautions we can. Without this we are going to be very restricted in what we can actually test.

(At this point the panel ended)

BIOASSAY OF FORMULATIONS OF BACILLUS THURINGIENSIS FOR USE IN FORESTRY: PANEL DISCUSSION OF THE ROLE OF THE BIOASSAY IN STANDARDIZING FORMULATIONS OF B. THURINGIENSIS^{1/}

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The panel discussed various aspects of Bacillus thuringiensis formulations and fermentations and concluded that the only means at present of standardizing these formulations or discovering more potent strains of the Bacillus is through carefully controlled bioassays.

Introduction -- Dulmage

The basic problem in the use of Bacillus thuringiensis (B.t.) for the control of either the gypsy moth, Lymantria dispar, or the spruce budworm, Choristoneura fumiferana, is not whether it can work -- it can, as I think that we have seen from the papers that we have heard during these meetings -- but whether it can work reliably. And difficult though it may be to achieve, "reliability" means that we must assure the user that the amount of activity present in a B.t. formulation is what the label says it is -- each and every time. This means that the quantity of delta-endotoxin in a formulation (i.e., the potency of a formulation) must always be the same, and that the remainder of the formulation will be assembled in such a way that the efficacy of the formulation will repeat from application to application.

Potency and efficacy depend on each other -- how much delta-endotoxin a formulation contains and how effectively a formulation performs are, and always will be, interdependent. If we restrict ourselves to a specific number of IU's/mg or ml in a series of formulations, the effectiveness of the formulations will then depend on the different qualities of the formulation ingredients. This concept frequently

gets lost in our consideration of B.t. (or, for that matter, any microbial insecticide). Most people are able to accept the concept that changes in composition of the carriers in chemical formulations can make formulations containing the same quantities of active chemical ingredients (say a synthetic pyrethroid) more or less effective in field applications. In the case of chemical insecticides, we realize that, to define a formulation, we need to know both the level of active ingredients and the recommended application rates of formulations of chemical insecticides like the synthetic pyrethroids. We accept this and agree that both are needed on the label. The same applies to a B.t. formulation. Just as in the case of a chemical insecticide, we also need to know both the level of active ingredients (IU/mg or ml) of the delta-endotoxins produced by B.t., and we need to know the recommended application rates of the B.t. formulations. Here too, both are needed on the label. I don't know why, but what seems clear and well understood and accepted in the case of chemical-based insecticides, is not clear, understood, or accepted in the case of B.t. formulations. In the case of B. thuringiensis, if formulations produced by two companies contain the same levels of delta-endotoxin as measured in bioassays, but have different effectiveness in the field so that the recommended application rates are different, then it is frequently claimed that the bioassays that determined the IU's/mg or ml of the B.t. put into the formulation must be wrong. It is then concluded that biological materials such as B.t. cannot be standardized.

This conclusion is not new -- it arose in the early days of the commercial production of B.t. Because of it, companies and scientists predicated much of their work on the belief that "there is no reliable bioassay of B.t." As a result, each company producing B.t. developed its own method of standardizing its product -- methods ranging from spore counts, to microscopic crystal counts, to bioassays against this insect species or that, to, I sometimes used to think, assessing which planet was in which sign of the zodiac at the time the formulation was prepared. This was wrong then -- and it is wrong now. Formulations of B.t. can be standardized, and once the effectiveness of a given composition of carriers and IU's has been determined, formulations can be made reproducible by assaying the quantity of delta-endotoxin contained in the formulation and keeping it constant. The user can rely on the IU's determined in a properly designed bioassay. The design of the bioassay -- and this will be covered in detail by Dr. Beegle, may have to be adapted to the situation -- certainly, Dr. Beegle and industry in a recent -- and I think outstanding -- cooperative study have greatly improved our bioassay procedures and our understanding of these procedures. Thanks to their work bioassays of even the newer flowable formulations are reliable, the IU's expressed on the label are accurate, and the efficacy of the product can be trusted. We have suffered in the past from the practice of each company designing its own bioassays and procedures. This led to confusion (and really to chaos) to the user, and,

^{1/}Revised and edited proceedings of a panel discussion held in conjunction with the meeting of CANUSA, Windsor Locks, CT, April 12, 1984.

as the user tried to follow IU's determined in different ways, he lost faith, not only in the formulation that he was using, but in B.t. itself.

"Trust" is not meant to imply that any one company might intentionally market an inferior product, disguising it with faulty assays. But, as will be seen, improper design of bioassays can lead to misleading potency determinations. There has to be some agreement between producers, the USDA (ARS and FS), and the government regulatory agencies as to what we are measuring and how we should measure it. We must not let the competitive urge lead us to forget how important the standardization of bioassay procedures between producers is. This point should be reiterated: Let each company go its own way and put its own IU's on its labels, and we are going to so confuse the user that his trust in B.t. will be destroyed.

Fortunately, the producers of B.t. realize this, and industry and the USDA, under the leadership of Dr. Beegle, has been exploring improved ways to standardize B.t. taking into account the various problems that have arisen in the standardization process, and Dr. Beegle will now discuss these problems and what is being done to coordinate bioassays.

Problems in Standardization -- Beegle

Formulations of B.t. are standardized in bioassays against a selected test insect. In these assays, the test insect is exposed to diet containing variable levels of the B.t. formulation and, after a suitable period of incubation, the percentage kill for each level is recorded, and the LC₅₀ of the formulation is determined. The LC₅₀ of the test formulation and the LC₅₀ of a standard reference material tested at the same time against the same population of insects are compared. Since the IU/mg of the standard is known, the potency of the formulation can be determined by the following formula:

Potency, IU/mg, test sample =

$$\frac{\text{LC}_{50} \text{ Standard} \times \text{Potency Standard, IU/mg}}{\text{LC}_{50} \text{ Sample}}$$

In 1971, representatives of the three commercial producers of B. thuringiensis in the United States and the USDA met in Brownsville, Texas, and agreed in principle to a standardized bioassay procedure using larvae of the cabbage looper, Trichoplusia ni, to standardize the potencies of their respective products (Dulmage et al. 1971). Because of the adoption by industry in 1970 of a much more potent strain of B. thuringiensis, which was of a different serotype than earlier B.t.'s, the Pesticide Regulation Division of the U.S. Environmental Protection Agency requested that a standard be produced and adopted which was the same serotype as that being commercially produced (subsp.

kurstaki). This was accomplished in 1972, when HD-1-S-1971 was adopted as the Primary U.S. Reference Standard with an assigned potency of 18,000 IU/mg (Dulmage 1973). Recently, the supply of HD-1-S-1971 became exhausted, and a new standard, labeled HD-1-S-1980, has been prepared and assigned a potency of 16,000 IU/mg after comparison with HD-1-S-1971 and E-61. Today all preparations of B. thuringiensis produced in the U.S. for use against lepidopterous larvae are standardized against either HD-1-S-1980, or an internal HD-1 standard which was initially standardized against HD-1-S-1971.

In 1980, a problem emerged in the standardization of lepidopterous-active B. thuringiensis preparations. The Brownsville USDA laboratory was contracted by the U.S. Forest Service to bioassay the tank mixes of the flowable B. thuringiensis products, Thuricide and Dipel, used in the CANUSA B. thuringiensis Core Tests. The potencies determined by Brownsville, using neonate T. ni larvae and diet containing antibiotic, were only 40-60% of the label values. Both commercial products were standardized using 4-day-old T. ni larvae and diet without antibiotic. In 1981, research was undertaken by the USDA and the Upjohn Co. to determine the reason for the difference. In these studies two preparations of B.t. from the Upjohn Co. (SOK W and SOK L) and two formulations from Abbott Laboratories (Dipel WP) were tested. The results are shown in Table 1. In the case of the SOK wettable powder (W) and liquid (L), it is clear that the use of 4-day-old larvae in the bioassay results in higher determined potencies than when neonate larvae are used. In the case of the Dipel wettable powders (WP), one of them (0452BJ) was larval age sensitive and the other (F-1980) was not. In my experience that is typical of Dipel products -- some are larval age sensitive and others are not.

In addition, the USDA and the Forest Service set up a blind test where differing amounts of viable HD-1-S-1980 were added to Sandoz and Abbott flowable carriers. These samples, along with flowable Dipel and Thuricide samples were coded and sent out for assay to the USDA laboratories in Brownsville, Texas, and Columbia, Missouri, and to Abbott and Sandoz. The results of these assays are presented in Table 2. Except for two values (2870 for Thuricide, and 16,100 for Dipel, the results in Table 2 for the commercial flowables substantiates the results observed in Table 1 concerning the commercial flowables: the use of 4-day-old larvae in the bioassay resulted in significantly higher potencies than when neonate larvae are used. It was shown by Beegle et al. (1981) that 1-day-old T. ni larvae respond the same as neonate larvae in B. thuringiensis bioassays. It is noteworthy that larval age did not significantly affect the potencies of the samples where HD-1-S-1980 was incorporated into the commercial flowable carriers. This indicates that the observed larval-age-difference effect on determined potencies is due to differences in the bacteria rather than in the formulation. In fact, Yamamoto (pers. comm.) has cautioned that anyone who uses the HD-1 isolate

Table 1. Effect of Larval Age and Antibiotic on Potency Determinations of Commercial *Bacillus thuringiensis* Products.^{a/}

Preparation	<i>Trichoplusia ni</i> Larval Age	Anti-biotic in Diet?	USDA Brownsville				Upjohn			
			No. Assay	X IU/mg or 1X10 ³ /ml	+ SD	% CV of Assays	No. Assays	X IU/mg or 1X10 ³ /ml	+ SD	% CV of Assays
SOK W 747 JF	neonate	yes	3	13,600	+ 814	6	5	11,600	+1910	16
SOK W 747 JF	neonate	no	3	15,400	+1510	10	6	13,400	+2040	15
SOK W 747 JF	4-day-old	yes	3	27,700	+5300	19		-		
SOK W 747 JF	4-day-old	no	4	30,100	+5370	18	7	36,300	+6930	19
SOK L 645 JB	neonate	yes	6	3,640	+ 692	19	8	2,950	+ 514	17
SOK L 645 JB	neonate	no	3	3,640	+ 369	10	4	3,700	+ 534	14
SOK L 645 JB	4-day-old	yes	3	6,310	+ 936	15		-		
SOK L 645 JB	4-day-old	no	5	7,850	+1310	17	6	9,420	+1260	13
Dipel WP 04523BJ	neonate	yes		-			9	12,300	+1670	14
Dipel WP 04523BJ	neonate	no		-			2	12,100	+1310	11
Dipel WP 04523BJ	4-day-old	no		-			3	24,300	+1580	6
Dipel WP F-1980	neonate	yes	3	14,800	+2280	15		-		
Dipel WP F-1980	neonate	no	4	16,300	+ 594	4		-		
Dipel WP F-1980	4-day-old	yes	3	12,000	+2490	20		-		
Dipel WP F-1980	4-day-old	no	4	11,500	+ 675	6		-		

^{a/} Taken from Beegle et al. (in press).

Table 2. Results of Blind USDA-Industry Bioassay Test.^{a/}

Laboratory	Larval Age	No. Assays	Range of CVs	IU/mg					
				01-S 1980	02-S 1980	03 Thuricide	04-A 1980	05 Dipel	06-A 1980
USDA-Brownsville	neonate	18-20	15-18	1700	2610	1290	4170	5630	5620
USDA-Columbia	1-day-old	3- 4	-	1660	2010	1380	4210	16,100	6620
Sandoz	4-day-old	-	9-19	1960	2760	3970	3310	8110	4520
Abbott	neonate	6-14	5-15	2340	2870	2870	3180	3720	3480
Boyce Thompson Calculated	-	-	-	1720	2570	3430	3810	8800	5800

^{a/} Lewis, F.B., Report on Blind BT Sample Bioassays, USDA-Forest Service, New Hamden, CT, 1982.

to study the genetics or chemistry of *B. thuringiensis* should keep in mind that there are differences in the plasmid and P-1 HPLC patterns among cultures labeled as HD-1.

Because of the discovery that the use of a standard does not correct for differences in assay procedures in all cases, the USDA and the U.S. producers and/or marketers of *B. thuringiensis* products held a meeting in 1982 and decided that we needed a new standardized lepidopterous *B. thuringiensis* bioassay that everybody would follow. The following summarizes the decisions reached at that meeting:

1. Rearing

Origin of *T. ni* colony, rearing diet, rearing conditions, and rearing techniques and procedures will not be standardized.

2. Bioassay

a. Diet - Brownsville diet without antibiotics or KOH.

- b. Diluent - deionized or distilled water.
- c. Sample homogenization - sonicate in bath sonicator for 5 min. at sonicator loading of 3 ml (container size)/watt.
- d. Number of dilutions - enough for a minimum of five on-curve dosage mortality points, at least two above and two below LC₅₀.
- e. Type of dilutions - 3:4 (75%).
- f. Diet incorporation - 1:10 with 55°C diet, mix for 2 min.
- g. Number of insects/dose - minimum 25.
- h. Age of larvae - 4-days-old at 30°C.
- i. Holding (infesting) density - multiply or singly.
- j. Holding time and temperature - 4 days at 30°C.

3. Potency Determinations

- a. Each preparation must be bioassayed at least three times over at least two days (three days preferable).

- b. A mean potency value for a preparation should consist of at least three potency values from valid assays whose group coefficient of variation is less than 20%.
- c. Valid assays are defined as those with a minimum of five on-curve points, with at least two above and two below the LC₅₀, significant regressions, significant F values, and 95% confidence values of less than a 3X range. Assays with atypical slopes, significantly high X²s, erratic points, or 95% confidence value ranges greater 2X, but less than 3X, should be discriminated against if necessary, but not be considered invalid.

Table 3 is presented to establish the validity of the determined potency of 16,000 IU/mg for the new U.S. *B. thuringiensis* HD-1 standard. E-61, which had an assigned potency of 1,000 IU/mg; HD-1-S-1971, which had an assigned potency of 18,000 IU/mg; and HD-1-S-1980 were concurrently bioassayed by four companies and USDA-Brownsville. On the basis of over 200 bioassays, it was determined that HD-1-S-1980 had a potency of 16,000 IU/mg. We have known for years that HD-1-S-1971 was not homologous with "normal" HD-1's in its activity towards larvae of *Heliothis virescens*. Since HD-1-S-1971 is a little over twice as active toward *H. virescens* larvae than most HD-1 preparations, the Tn/Hv ratio (the ratio will be discussed in the next section, but represents the comparison of potencies determined against *T. ni* and those determined against *H. virescens*) of most HD-1 preparations is a little over 2. HD-1-S-1980 appears to be homologous in this respect to most HD-1 preparations, as the mean Tn/Hv ratio of 87 HD-1 preparations assayed against this standard at Brownsville was 1.04.

Reproducibility and the Activity Ratio -- Dulmage

One of the most important and fascinating aspects of the delta-endotoxins produced by *B. thuringiensis* is that different subspecies -- and, indeed, isolates -- of this *Bacillus* species, kill different insects or differ in their relative activities against them. Dr. Beegle has discussed the relative differences found between different isolates of subsp. *kurstaki* in their activities against *T. ni* and *H. virescens*. This can lead to two legitimate concerns: (1) Will the same endotoxin be produced in repeat fermentations, or will the type of endotoxin vary? (2) Can we use one insect species in our bioassays -- and does that have to be the target insect? All this, of course, leads to the label and what influence all this has on what is put on the label.

These are important questions and pose serious problems. Table 4 illustrates the differences between subspecies and isolates. The table shows the spectra of insecticidal activity of a series of different *B.t.*'s produced by subsp. *alesti*, *kurstaki* (k-1), *kurstaki* (k-73),

Table 3. Standardization of HD-1-S-1980.

Sample	Standard	IU+SD	CV	No. Assays
<u>Abbott Laboratories</u>				
E-61	HD-1-S-1971	853+ 150	17	14
E-61	HD-1-S-1980	827+ 145	17	14
HD-1-S-1971	E-61	21,800+4390	20	14
HD-1-S-1971	HD-1-S-1980	17,500+1560	9	14
HD-1-S-1980	E-61	19,900+3640	18	14
HD-1-S-1980	HD-1-S-1971	16,000+2770	17	64
<u>Biochem Products</u>				
E-61	HD-1-S-1971	758+ 191	25	9
E-61	HD-1-S-1980	683+ 342	50	9
HD-1-S-1971	E-61	24,600+4600	19	9
HD-1-S-1971	HD-1-S-1980	16,000+4090	26	9
HD-1-S-1980	E-61	25,700+6180	24	9
HD-1-S-1980	HD-1-S-1971	19,000+4390	23	9
<u>Sandoz, Inc.</u>				
TS ^{a/}	E-61	21,500+2040	4	13
HD-1-S-1971	E-61	16,600+5820	15	8
HD-1-S-1971	TS	15,900+5760	17	12
HD-1-S-1980	E-61	14,200+2440	7	7
HD-1-S-1980	TS	14,900+3230	11	36
HD-1-S-1980	HD-1-S-1971	14,700+4030	11	6
<u>Upjohn Co.</u>				
E-61	HD-1-S-1971	1,135+ 381	33	3
E-61	HD-1-S-1980	1,319+ 260	20	3
HD-1-S-1971	E-61	17,000+4950	29	3
HD-1-S-1971	HD-1-S-1980	18,000+3592	20	8
HD-1-S-1980	E-61	12,400+2120	18	3
HD-1-S-1980	HD-1-S-1971	16,500+3070	19	8
<u>USDA Brownsville</u>				
E-61	HD-1-S-1980	1,280+ 247	19	32
HD-1-S-1971	HD-1-S-1980	21,300+4170	20	42
HD-1-S-1980	E-61	12,900+2570	20	30
HD-1-S-1980	HD-1-S-1971	15,700+1990	13	23
<u>All Sources Combined: Nonweighted</u>				
E-61		980+ 260	27	84
HD-1-S-1971		18,700+3070	16	119
HD-1-S-1980		16,500+3800	23	209
<u>All Sources Combined: Weighted^{b/}</u>				
E-61		1,010+ 392	39	84
HD-1-S-1971		19,600+4360	22	119
HD-1-S-1980		16,000+3139	20	209

^{a/} Sandoz internal standard.

^{b/} Weighted as to number of assays.

galleriae, and aizawai. As the table shows, there is a wide difference between them in their activities towards lepidoptera and in their relative activities against different insect species when they are active against them. (One variety, not included in this table, is not even active against lepidopterous insects, although it is extremely active against mosquitoes and aquatic black flies.) With this proliferation of different spectra, the problem of standardization seems almost insurmountable. Industry, Dr. Beegle, and myself all agree on the desirability of using T. ni as the assay insect of choice for the present commercial delta-endotoxins active against lepidopterous insects. Yet, as the table shows, the existence of delta-endotoxins with different spectra of insecticidal activities makes it perfectly possible that the potency of delta-endotoxins produced by two isolates of B.t. may be the same when measured against T. ni but may differ considerably when evaluated against L. dispar. However, if the same type endotoxin is produced in replicate fermentations of each of these isolates of B. thuringiensis, then our problem merely parallels the case with different formulations of chemical insecticides, where the same quantities of a chemical in different formulations may differ widely in their effectiveness in control of a target insect. In the case of the chemicals, the differences arise from differences in their formulation. Microbial formulations may vary for this reason too, but with microbials, the differences may also reflect differences in the chemical structure of the delta-endotoxins produced by different isolates, i.e., the basic activity of the endotoxin. With our present knowledge, we do not know what these differences are -- remember, we cannot weigh or identify in a quantitative chemical assay the delta-endotoxins that we are producing -- we only measure their activities: i.e., what insects they kill and how well they kill them.

Table 4. Spectra of Activities of Selected Subspecies of Bacillus thuringiensis.

Culture No.	Variety	Crystal Type	Potency - IU/mg Measured vs.:			
			<u>T. ni</u>	<u>H. vir.</u>	<u>H. cunea</u>	<u>B. mori</u>
HD-1	<u>kurstaki</u>	<u>k-1</u>	39800	15400	47200	50500
HD-73	<u>kurstaki</u>	<u>k-73</u>	23100	34500	12800	Inact
HD-263	<u>kurstaki</u>	<u>k-1</u>	39600	54600	18100	18400
HD-70	<u>alesti</u>	<u>ale</u>	Inact	Inact	47900	34000
HD-160	<u>galleriae</u>	<u>gal</u>	5920	894	23800	4100
HD-275	<u>aizawai</u>	<u>aiz</u>	8110	969	19500	44400

To illustrate the problem, let us create a hypothetical case of two formulations of B.t., each containing, say, 10,000 IU/mg of activity as measured against T. ni. However, one is several times more active against L. dispar than the other. How do we standardize formulations of each for use against this insect? Must we measure each and every formulation only against

every target insect that we desire to kill? Such a path will lead to chaos and confusion -- and very likely to the need of a multiplicity of labels for each B.t. formulation. Fortunately, there seems to be an alternative.

Potencies of formulations of B.t. delta-endotoxins are determined relative to a selected reference standard, as Dr. Beegle has discussed. If the formulation being tested contains the identical endotoxin to the standard, then it will not matter which insect species is used in the bioassay. However, if the test endotoxin and the standard endotoxin are not homologous -- i.e., if they differ in their spectra of activity -- then the choice of insect will have a profound influence on the IU's determined. For example, a formulation of subsp. alesti would be considered inactive if bioassayed against T. ni, but would be considered very active if assayed against the webworm, Hyphantria cunea. In a less extreme example, a formulation of subsp. kurstaki (k-73) might have a potency of 20,000 IU/mg if measured against T. ni, but have a potency of 40,000 IU/mg if measured against H. virescens. By constructing a fraction from these data, we can derive an "Activity Ratio." An activity ratio of a formulation is simply a straight-forward comparison of the activity (in IU's) against two different insect species. Thus in our example here, the Tn/Hv activity ratio is simply determined by dividing the activity determined against T. ni by the activity found against H. virescens, as shown in the following equation:

$$\text{Tn/Hv Activity Ratio} = \frac{20,000 \text{ IU/mg}}{40,000 \text{ IU/mg}} = 0.500$$

The ratio will, of course, vary with the endotoxin being tested and with the insect species being used. The value of the ratio thus becomes an accurate mathematical definition of a portion of the spectrum of activity of a delta-endotoxin.

Encouragingly, our data so far leads to the conclusion that, while the spectra of activity of the delta-endotoxins produced by different isolates may differ widely, the spectra of activity of the delta-endotoxins produced under different fermentation conditions by a single isolate of B.t. are reproducible. This is shown for four formulations in Table 5. If this is true -- and we believe that it is -- then, if we know the relative activities of an endotoxin against T. ni and the gypsy moth, we can assay against the cabbage looper and reliably predict the potency of the endotoxin against the gypsy moth. Once we are satisfied that this is so, then the "active ingredients" of B.t. on a label of a forestry formulation can be safely listed as IU/mg vs. T. ni and represent how much B.t. was put into the formulation, and the efficacy of the formulation can be expressed in pints or pounds/acre. Activity and efficacy are being presented on the label in the same way as a chemical -- and, once we have gotten used to this, it should be no more of a communication than with chemicals.

Table 5. Reproducibility of Activity Ratios.

Culture No.	Number of Formulations	Avg. Tn/Hv Ratio	Coefficient of Variation
HD-1	60	2.14	0.25
HD-241	26	0.63	0.24
HD-244	26	1.54	0.23
HD-263	136	0.44	0.29

Thus it is my view that an assay insect does not need to be the target insect, but need only be a convenient, easy-to-rear-and-use insect which is susceptible to the delta-endotoxin in the product. The cabbage looper seems to fit these characteristics. However, it may very well happen that someone will discover a new B.t. that is very effective against L. dispar that may not be active enough against T. ni for this insect to serve as an assay tool. In such a case, of course, another insect species may be needed. However, at present no such B.t. is known, and T. ni should be satisfactory for these assays. The label should then read in IU's as determined against this insect. The differences in efficacy that may occur should be shown in the recommended application rates, not as different IU's. It has been suggested that one could include on the label a Tn/Ld Activity Ratio as a parenthetical addition. However, this may be confusing and of little value to the user. Thus it is our belief that the bioassay against T. ni should remain the key for standardizing B.t. in forestry formulations.

Miscellaneous Aspects of Evaluating New Isolates of B.t. -- Dubois

In a paper that I presented earlier in this meeting, I discussed some of our research seeking new isolates of B.t. with increased activity over HD-1 against L. dispar. Drs. Dulmage and Beegle have just discussed their work with bioassays and activity ratios, particularly as they relate to T. ni and H. virescens. In this portion of our panel program, I would like to discuss how some of their observations relate to our experience with L. dispar.

Tn/Hv Ratios

A few years ago, our FS laboratories at Hamden, CT, joined in an International Screening Program to survey the spectra of insecticidal activities of about 350 isolates of B. thuringiensis. The results of this survey were very complex and will not be discussed here (for more details, see Dulmage et al. 1981). One of the observations that was reported was that the Tn/Hv activity ratios of formulations derived from isolates of subsp. kurstaki and which contained the k-1-type crystal were about 2.0. Formulations of this subspecies which contained the k-73-type had Tn/Hv ratios of about 0.40. The difference in the two types seemed to lie in the activity of k-73 formulations against H.

virescens. Simply, the k-73 endotoxin was more active against H. virescens than was the k-1 toxin. The parallel to L. dispar was interesting. When we examined the more potent isolates of B. thuringiensis, we found that these formulations had Tn/Hv ratios of about 2.0, belonged to subsp. kurstaki, and contained the k-1 crystals. Interestingly, those isolates of subsp. kurstaki that produced k-73-type crystals were not as active vs. L. dispar. These generalities should not be taken to mean that all isolates of a given subspecies will have the same potency. Some formulations will be very active, some will have little or no activity, and the activities of others will lie somewhere in between.

Reproducibility of the Response of L. dispar to B.t.

The primary need for an accurate B.t. bioassay is, of course, a supply of uniform, healthy, bioassay insects. Even with such an insect, however, the assay will not be reliable if the response of the insect to B.t. formulation changes according to the source of the insect. To see if this were a serious problem in assays with L. dispar, we have compared the response of a series of sources of L. dispar to the two standard B.t. formulations, HD-1-S-1971 and HD-1-S-1980. The cultures of L. dispar studied were diverse and included the New Jersey strains in our laboratory and the F₁₈ through F₂₄ generations of our laboratory colony. The responses of L. dispar to these standards were evaluated by the LC₅₀'s determined for the standard against the various insect cultures. The results of these assays are summarized in Table 6. The responses were very uniform, and what variations were observed seemed to be due to the diet, not to any change in the response of the insects. I think that we have reasonable assurance that the source of the L. dispar does not affect the response to B.t. in our bioassays.

These tests were all run with laboratory-reared insects. They leave open a very important question -- How do the responses of laboratory insects compare with wild insects? -- i.e., do we need to maintain a laboratory colony generation after generation, or could we collect wild egg masses in the field each year and use these for our bioassays? The study is not yet completed, but we have examined the responses of insects reared from egg masses of wild sources of L. dispar collected in Connecticut, New Hampshire, New York, Massachusetts, and Pennsylvania. We found some minor differences in the responses of the different insect strains (which might very well have been due to diet again), but overall, the LC₅₀'s determined for the standard formulations did not vary much with insects of different origin. This is not to say that wild insects are the insect of choice -- one must consider the risk of results being distorted by the presence of unrecognized disease in the wild culture.

Table 6. Slopes and LC₅₀ of the Bacillus thuringiensis Standards, HD-1-S-1971 and HD-1-S-1980, Bioassayed Against the New Jersey F₁₈ to F₂₄ Generations of Lymantria dispar L. Continuously Reared on Artificial Diet.

Fermentation	No. of Bioassays	Slope	C.V.	LC ₅₀ (µg/ml)	C.V.
HD-1-S-1971 (18,000 IU/mg)					
F ₁₈ (1979-1980)	4	4.25	0.16	7.82 ^a / _a	0.09
F ₁₉ (1980)	4	4.54	0.20	5.83ab	0.27
F ₂₁ (1980)	28	4.72	0.20	5.70ab	0.09
F ₂₂ (1981)	5	4.86	0.27	7.38ab	0.38
HD-1-S-1980 (16,000 IU/mg)					
F ₂₂ (1981)	24	4.62	0.21	5.33ab	0.33
F ₂₃ (1982)	29	4.87	0.21	5.01ab	0.25
F ₂₄ (1983)	13	5.09	0.16	5.24ab	0.25

^a/ Numbers followed by the same letter are not significantly different from each other at the 5% level (Scheffe's method for all possible contrasts).

Table 7. LC₅₀ of Bioassays of Several Sources of F₁ Generations of Instar II Lymantria dispar L. fed on Fresh and on Old Diet.

Larvel Source	Diet	LC ₅₀ (µg/ml of diet) on Dates:					
		2/9	3/13	3/14	3/24	3/28	3/31
New Jersey	fresh	6.9			5.9	5.0	6.8
F ₂₆	old		17.8	13.0			
Cockaponset, CT	fresh	12.4			---	---	8.3
F ₁	old		13.6	21.6			
Storrs, CT	fresh	7.9			7.9	6.9	---
F ₁	old		15.3	27.3			
New Hampshire	fresh	8.4			6.3	6.4	---
F ₁	old		13.1	16.0			
Mashpee, MA	fresh	8.3			6.9	7.4	---
F ₁	old		15.7	20.6			
Pennsylvania	fresh	10.6			6.7	7.9	
F ₁	old		9.2	34.6			

Influence of Diet on the LC₅₀

The composition of the diet can affect the observed LC₅₀'s of B.t. formulations. This was discovered early in our program. We began then, and still do today, to buy a premixed insect diet from a single supplier. Over a long period of time, we amassed considerable experience in just where the LC₅₀'s of our standard formulations and test samples would be. We recently received a new shipment of diet that was mistakenly contaminated with antibiotics. When we attempted to use this diet, we found that the LC₅₀'s of both the standard and the test samples were very high -- it appeared that our materials had lost activity. When we used antibiotic-free diet that had been stored frozen for 18 months, the LC₅₀'s were again very high, indicating a loss of activity of the B. thuringiensis preparations, an increased resistance of the insect, or an incompatibility to the diet. Meanwhile, we received a new batch of diet, and the results of our assays dropped, returning to the "normal" range (Table 7). Thus the cause of the erratic LC₅₀'s lay, not in the insect, but in the diet.

Influence of Formulation on the Bioassay

Earlier, Dr. Beegle described some of the problems that they encountered with bioassays of flowable formulations and the influence of insect age and the presence or absence of antibiotic in the diet. We have had similar problems. During the field work last year in Maine, we used drums of Thuricide 32LV and SAN 415 32LV. We sent samples to Donald Hostetter in Columbia, Missouri, for him to assay by his surface contamination technique against T. ni (different from the usual T. ni assays), while we assayed duplicate samples against L. dispar. The assays obtained were very similar to each other and to the results obtained the previous year at Brownsville against T. ni.

This led us to believe that the causative mechanism for the discrepancies observed in the bioassays against L. dispar was the changes in the diet and larval age in the various assays. However, the composition or structure of the delta-endotoxins in the various B.t. isolates may also play a role. This observation may be reinforced by the assay results obtained with two

experimental flowable concentrates prepared by Sandoz for a comparative study of HD-1 and NRD-12 (HD-945). When the concentrates of the two strains were bioassayed against T. ni, both were reported by Sandoz to contain 32 BIU/gal, but by Dr. Hostetter's assays against T. ni were found to be only 14 BIU/gal -- a discrepancy vs. the label potency similar to that found in our previous assays of commercial concentrates. However, when these two flowables were bioassayed against L. dispar, the HD-1 concentrate assayed 15 BIU/gal (similar to the assays vs. T. ni), while the NRD-12 concentrate assayed 42 BIU/gal (nearly 3 times higher than the HD-1 concentrate with an "R-value" of 2.3). Similar differential assays were found in the tank mixes prepared from these concentrates: Assays against the HD-1 mix were essentially the same regardless of which insect was used in the assay; NRD-12 again assayed nearly 3 times higher against L. dispar (R-value = 2.9) (Table 8). Thus the two materials were similar when measured against T. ni, but different when measured against L. dispar -- further evidence of the importance of Dulmage's warning about the necessity for monitoring activity ratios in these studies.

Table 8. Differences Between the Potency Estimates of Thuricide 32LV (HD-1) and SAN 415 32LV (NRD-12) and their Diluted Tank Mixes^{a/} when using Lymantria dispar and Trichoplusia ni.^{b/}

Potency Estimates in BIU/gal				
Source of Concentrate	<u>Lymantria</u> <u>dispar</u>	R ^{c/}	<u>Trichoplusia</u> <u>ni</u>	R
Concentrate:labeled 32 BIU/gal				
Thuricide 32LV	18.1	2.3	13.7	1.1
SAN 415 32LV	42.2		15.3	
Tank mixes:calculated 24 BIU/gal				
Thuricide 32LV	5.4	2.9	9.5	1.2
SAN 415 32LV	15.8		11.4	

^{a/} Samples were from the spruce budworm spray test in Maine, 1983. Tank mixes are from the concentrates diluted with water.

^{b/} T. ni assays done by D. Hostetter, USDA, ARS, Columbia, MO.

^{c/} $R = \frac{LC_{50} \text{ NRD-12}}{\text{Potency HD 1}}$

Summary

The results of the work discussed in these papers, combined with the results previously reported in the literature, show very strong evidence that, at our present stage of knowledge, it is essential that we rely on a bioassay as our only means of standardizing products formulated from B. thuringiensis fermentations. The results also indicate the need for a standard in the

evaluation of these bioassays, and finally, show the value of activity ratios as means of discriminating between the delta-endotoxins produced by the various isolates of B. thuringiensis. The reproducibility of these activity ratios, in particular the relative activities of L. dispar vs. T. ni, confirms that one insect species (e.g., T. ni) can be used to standardize a formulation against another insect species (e.g., L. dispar) with confidence that the relative activities will extrapolate between insect species.

Joint Statement by Panel Members -- Dulmage, Beegle, Dubois

We find no fault with the use of T. ni as an assay insect for standardizing commercial formulations of B. thuringiensis (although care must be taken to develop a proper protocol for these assays, as shown by Beegle in his talk), and, since its use is so widely accepted, we recommend this insect for these assays. We also recommend the use of HD-1-S-1980 as a standard in these assays. We disagree with the use of spore counts as a substitute for these bioassays, since we see no correlation at all between spore counts and insecticidal activity. The spore count may serve a purpose in following the immediate dispersal of a spray in test application, but not in following the potency or persistence of the B. thuringiensis formulations.

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Summary

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The theme running through all sessions of the symposium was that B.t. is an effective and reliable material for use in management of the gypsy moth and spruce budworm. This new status is the result of recent developments in the use of increased dosages, finer droplet deposition, ULV application rates, and competitive costs.

The symposium reaffirmed the outcome of several recent conferences on microbials by identifying two major areas in which continued international cooperative research and development is needed; (1) molecular biology and modification to develop more virulent strains of the pathogens; and, (2) more reliable formulation, application, and deposition technology.

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Northeastern Forest
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Managing Cavity Trees for Wildlife in the Northeast

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Abstract

This paper is a guide for woodland owners, managers, or arborists who want to provide key habitat components for northeastern cavity-nesting birds and mammals that use tree dens. Methods for creating and maintaining cavity trees, snags, and den trees are described.

Introduction

Dead trees and trees that contain decayed wood provide shelter for approximately a fourth of the forest wildlife species of the Northeast (Fig. 1). Both birds and mammals use cavities in such trees for shelter from the weather, to escape from predators, for foraging and caching food, and most importantly for producing and rearing young.

For years, cavity and den trees have been removed routinely both during timber management operations because they were thought to harbor diseases and insect pests, and in cities and towns because they were thought to be unsightly or hazardous. Wolf trees, likewise, have been removed routinely during timber management because their wide-spreading crowns suppressed other trees. These practices are starting to change because land managers and arborists now realize that most species of birds that use cavity trees feed primarily on insects, and thereby help prevent insect outbreaks. Also, public concern for the welfare of cavity-nesting wildlife has increased in recent years.



Figure 1.—Cavities in living, dead, and dying trees are used by many species of wildlife. These sugar maple trees have provided dens for many mammals.

How Cavities Form in Trees

Natural cavities develop when part of a tree dies or is injured. Death or injury can result from fire, insect attack, wind, snow or ice storms, logging wounds, herbicides, or other causes. Decay-causing fungi become established in tree wounds. Woodpeckers also create cavities when they excavate nesting, feeding, or roosting holes.

When a branch or a root dies, or when a tree is injured and infected, the tree responds by forming firmer boundaries to contain the injured and infected tissues or to resist the spread of infecting organisms. This defense process of boundary-setting is called compart-

mentalization. Boundaries and boundary-setting are the keys to understanding the development of cavities in trees.

The barrier zone is the tree's major defense boundary because it separates the older infected wood from the recently formed healthy wood. For example, if a tree is injured and infected when it is 4 inches in diameter, the greatest diameter of decayed wood will be 4 inches—about the right size for nest excavation by a downy woodpecker (*Picoides pubescens*). Organisms seldom spread beyond the barrier zone.

After branches and roots die, and after wood is injured by mechanical wounds, many organisms infect the dying and exposed tissues. Bacteria, nondecay-causing fungi, and decay-causing fungi are the major microorganisms that first interact with the tree. Discoloration and decay form as wood cell walls are broken down by microorganisms. As the decay process proceeds, many other organisms enter, such as insects and nematodes. The wood within the boundary set by the tree is slowly digested until a hollow results (Figs. 2, 3, 4).



Figure 2.—Dissection of a hemlock that was wounded by a black bear (see Figure 7). The wood sections show that the diameter of the tree at the time of wounding was the greatest diameter of decayed wood. As the wood breaks down, a cavity approximately 10 inches in diameter will develop in the tree.



Figure 3.—Dissection of a sugar maple shows the internal column of decayed wood. The diameter of the internal column was the diameter of the tree at the time of wounding at the base and above at 8 feet.

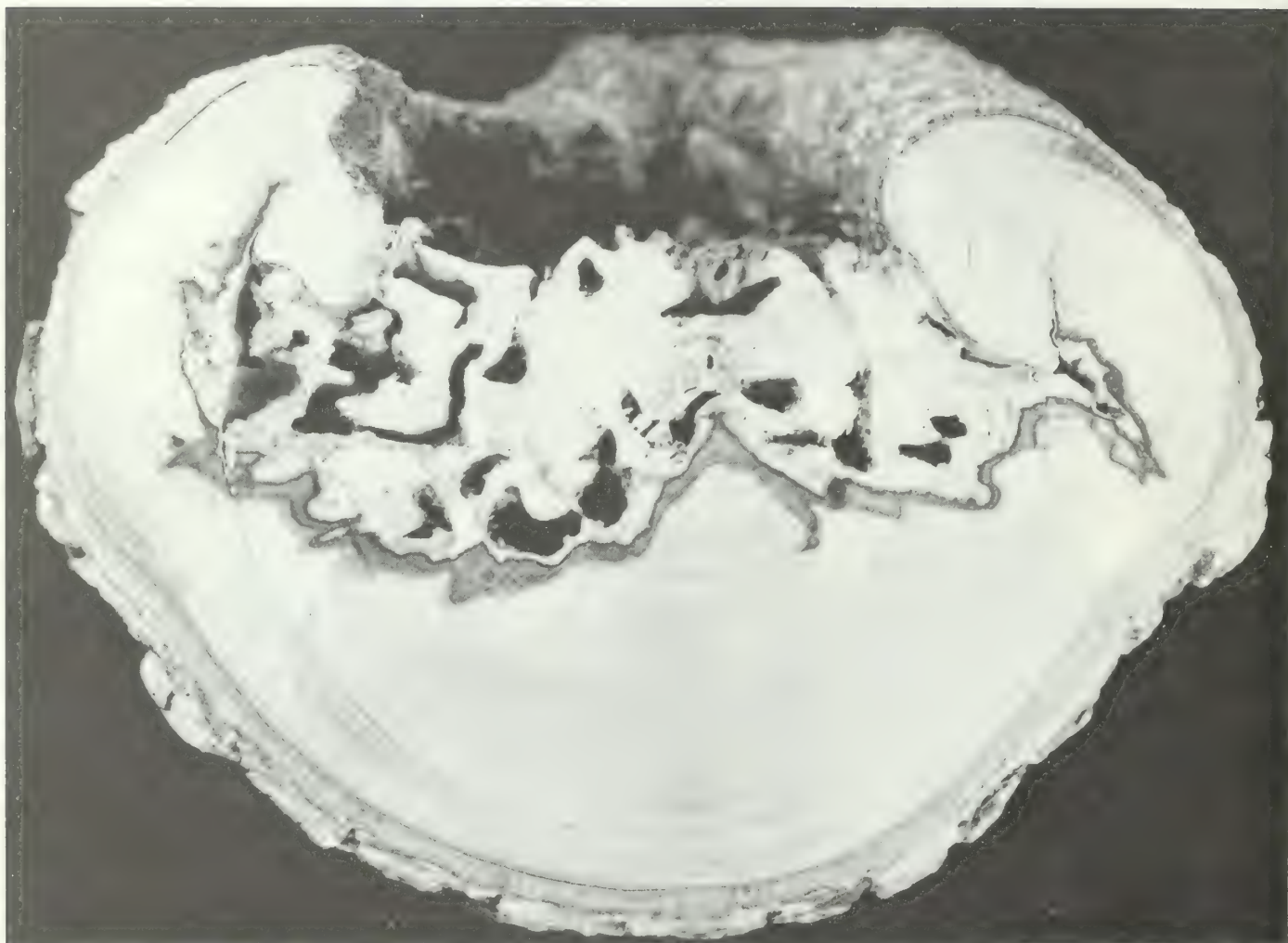


Figure 4.—The wound in this sweetgum was caused by a beaver. The decayed wood was within the diameter of the tree at the time of wounding. Note the barrier zone that formed completely around the trunk. The decay in time would have developed within the limits of the barrier zone. The barrier zones make cavities possible in trees.

But long before hollows form, in many trees woodpeckers may begin to either excavate the infected wood to form a cavity, or to drill into sound wood that surrounds the column of infected wood, and then into the infected wood (Fig. 5).

When leaders or main stems break or die on trees, a new leader may develop from a lower branch that is still alive. The stub of the old leader is called a stem stub. The column of decayed wood associated with stem stubs will be the diameter of the leader at the time of death, and the column will develop downward. As columns of decayed wood progress to hollows, they become ideal dens for many mammals. The cavities are most suitable when the leader was bent before it died—water does not flow into such cavities (Fig 6).

Often wounds occur at the base of large trees (Figs. 7 and 8). When the tree has the capacity to continue to grow, the diameter of the tree at the time of wounding will be the diameter of the defect. Such a situation can lead to the development of a cavity tree.

Trees survive after injury and infection because they wall off the infected wood. The boundary-setting process makes cavities possible in living trees. Knowing this, it is possible to regulate number and size of desired cavities for wildlife. For example, if an animal must have a cavity 4 inches in diameter, then some wounding must occur when the tree is 4 inches in diameter. Compartmentalization does give us new opportunities for wildlife management.



Figure 5.—Dissection of an aspen that was abandoned as a nesting tree by a yellow-bellied sapsucker. The sapsucker often selects aspen for nesting trees, especially trees that are greater than 10 inches d.b.h. Such trees often have large columns of firm decayed wood associated with canker rot fungi as shown here.



Figure 6.—Large cavity in a beech associated with a decayed stem stub that followed the decay of the leader when it was approximately 6 inches in diameter. The curved hollow is fine for cavity dwelling wildlife. Note also the sound roof to the cavity.



Figure 7.—Basal wound on western hemlock made by a black bear. Such wounds often start the processes that can lead to basal cavities.



Figure 8.—The wound on this small sugar maple was caused by red squirrels gnawing the stem. The wound could be the start of a future cavity.

Effect of Degree of Decay

Depending on their size, degree of decay, cause of injury or death, and location, cavity trees are used by various wildlife species for several purposes (Table 1). As a tree slowly dies and decays, it goes through several successional stages that are used by different wildlife groups in turn (Fig. 9). After a tree dies, the bare branches provide perch sites for predators such as hawks and other raptors as well as flycatchers. Perches that project

above the surrounding forest canopy or exist in clearings are used as lookouts for prey by birds such as American kestrels (*Falco sparverius*), Cooper's hawks (*Accipiter cooperii*), sharp-shinned hawks (*Accipiter striatus*), and broad-winged hawks (*Buteo platypterus*). The existence of such perches is a major factor in the use of a woodland by these birds. Flycatchers, likewise, use strategically located perches: Eastern phoebes (*Sayornis*

phoebe), kingbirds (*Tyrannus tyrannus*), and great crested flycatchers (*Myiarchus crinitus*), least flycatchers (*Empidonax minimus*), and olive-sided flycatchers (*Contopus borealis*) catch or "hawk" flying insects, returning after each sally to the same perch. These perches, whether above or below the forest canopy, are important habitat components as they largely determine whether these species are present or absent.

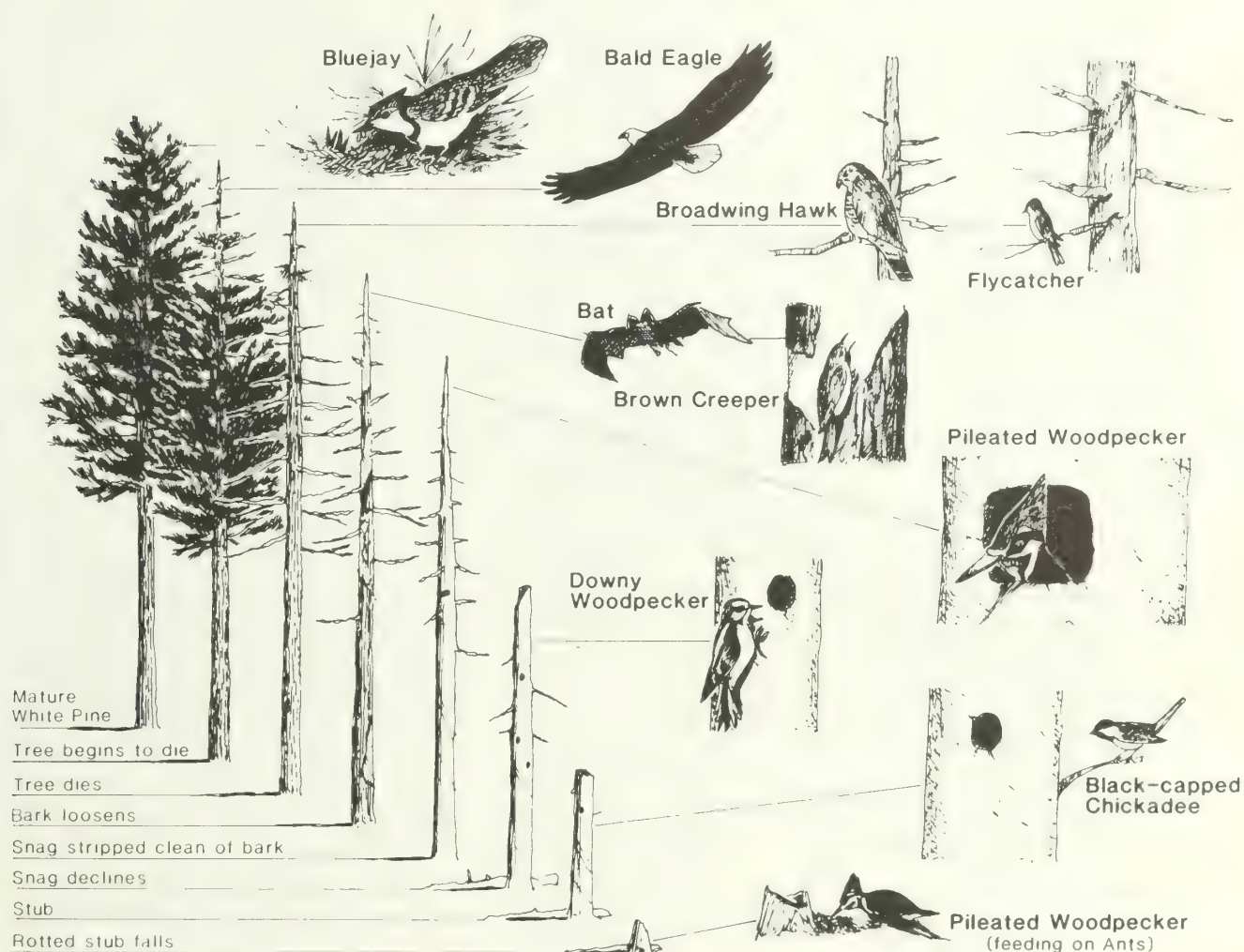


Figure 9.—Wildlife use changes as trees decay.

Table 1. Preferred habitat and use by cavity-nesting birds

Species	Tree				Use			
	Live, decayed	Dead, hard	Dead, soft	Best d.b.h	Perch- ing	Feed- ing	Nest- ing	Roost- ing
<i>Inches</i>								
PRIMARY EXCAVATOR								
Red-headed woodpecker <i>Melanerpes erythrocephalus</i>	X	X		20	X	X	X	X
Red-bellied woodpecker <i>Melanerpes carolinus</i>	X	X	X	16	X	X	X	X
Yellow-bellied sapsucker <i>Sphyrapicus varius</i>	X			12	X	X	X	X
Downy woodpecker <i>Picoides pubescens</i>	X		X	8	X	X	X	X
Hairy woodpecker <i>Picoides villosus</i>	X	X		12	X	X	X	X
Three-toed woodpecker <i>Picoides tridactylus</i>	X	X		10	X	X	X	X
Black-backed woodpecker <i>Picoides arcticus</i>	X			10	X	X	X	X
Northern flicker <i>Colaptes auratus</i>	X	X	X	12	X	X	X	X
Pileated woodpecker <i>Dryocopus pileatus</i>	X	X		20	X	X	X	X
Black-capped chickadee ^a <i>Parus atricapillus</i>			X	4			X	X
Boreal chickadee <i>Parus hudsonicus</i>			X	4			X	X
SECONDARY USER								
Wood duck <i>Aix sponsa</i>	X	X		20 +			X	
Common goldeneye <i>Bucephala clangula</i>	X	X		20 +			X	
Hooded merganser <i>Lophodytes cucullatus</i>	X	X	X	20			X	
Common merganser <i>Mergus merganser</i>	X	X		20			X	
Turkey vulture <i>Cathartes aura</i>	X	X	X	20 +	X		X	
American kestrel <i>Falco sparverius</i>		X		12 +	X		X	
Merlin <i>Falco columbarius</i>	X	X		20	X		X	
Common barn-owl <i>Tyto alba</i>	X	X		20 +	X		X	X
Eastern Screech-owl <i>Otus asio</i>	X	X			X		X	X
Barred owl <i>Strix varia</i>			X	20			X	
Northern Saw-whet owl <i>Aegolius acadicus</i>		X	X	12 +	X		X	X
Great-crested flycatcher <i>Myiarchus crinitus</i>	X			12 +			X	
Purple martin <i>Progne subis</i>		X		12 +			X	
Tree swallow <i>Tachycineta bicolor</i>		X		8	X		X	
Tufted titmouse <i>Parus bicolor</i>			X	6			X	X
Red-breasted nuthatch <i>Sitta canadensis</i>		X	X	12		X	X	X
White-breasted nuthatch <i>Sitta carolinensis</i>	X			12		X	X	X
Brown creeper <i>Certhia americana</i>	X	X		8 +		X	X	X
House wren <i>Troglodytes aedon</i>	X	X	X	6 +		X	X	X
Winter wren <i>Troglodytes troglodytes</i>			X	8 +			X	
Eastern bluebird <i>Sialia sialis</i>		X	X	8 +		X	X	
Prothonotary warbler <i>Prothonotaria citrea</i>			X	8 +			X	

^a May also be a secondary cavity user

Further decomposition of the tree results in a transitory "loose bark" stage. This sloughing bark provides the nest site for the brown creeper (*Certhia americana*) and roosts for bats (Tables 1 and 2).

Primary excavators—essentially the woodpeckers—usually excavate cavities when decay is present in the stem. Trees with central columns of decay resulting from stem stubs are readily excavated by woodpeckers, especially downy, hairy (*Picoides villosus*), and pileated (*Dryocopus pileatus*) woodpeckers and northern flickers (*Colaptes auratus*). All species of woodpeckers that occur in the Northeast, except the yellow-bellied sapsucker (*Sphyrapicus varius*) and black-backed woodpecker (*Picoides arcticus*)—which use only live trees—excavate nest cavities in live or dead trees. But decay columns in live trees, especially those resulting from stem stubs, seem to be preferred. The hard exterior wood protects the easily excavated nest cavity. These excavated cavities are subsequently used by the so-called secondary cavity nesters—the birds that we commonly attract with nest boxes (Table 1).

After a standing dead tree has decayed to the point where most of the branches have fallen, it is called a snag if it is at least 20 feet tall, a stub if shorter. The soft, punky snag or stub in the final stages of decay is used as a foraging site by many insectivorous birds, and as a nest site by black-capped chickadees (*Parus atricapillus*), that do not chisel cavities as woodpeckers do, but merely pick out the soft punk to form a cavity.

Once the rotted stub falls, invading carpenter ants and other insects provide an important food source for pileated woodpeckers. Many species of amphibians and reptiles live and forage in and under the moist, soft, rotting wood. Many small mammals are also associated with down logs (Table 2).

Table 2.—Tree den or roost characteristics of New England mammals

Species	Characteristic
Virginia opossum <i>Didelphis virginiana</i>	Tree cavity or hollow-log den
Little brown myotis <i>Myotis lucifugus</i>	Hollow-tree roost
Keen's myotis <i>Myotis keenii</i>	Roost under loose bark of dead tree
Indiana myotis <i>Myotis sodalis</i>	Bear young in hollow tree, or under loose bark
Silver-haired bat <i>Lasionycteris noctivagans</i>	Roost in tree cavity or under loose bark
Big brown bat <i>Eptesicus fuscus</i>	Roost in hollow tree
Eastern chipmunk <i>Tamias striatus</i>	Den in or under old logs
Gray squirrel <i>Sciurus carolinensis</i>	Den in cavities in tall hardwood trees
Red squirrel <i>Tamiasciurus hudsonicus</i>	Den in tree cavity—conifer preferred
Southern flying squirrel <i>Glaucomys volans</i>	Den in tree cavities or woodpecker holes in mature woodland
Northern flying squirrel <i>Glaucomys sabrinus</i>	Den in tree cavities or woodpecker holes in mature woodland
Southern red-backed vole <i>Clethrionomys gapperi</i>	Uses mossy logs, fallen trees for cover
Porcupine <i>Erethizon dorsatum</i>	Den in cavity in large trees
Gray fox <i>Urocyon cinereoargenteus</i>	Den in hollow logs, tree cavities
Black bear <i>Ursus americanus</i>	Den under fallen trees, in large hollow logs
Raccoon <i>Procyon lotor</i>	Den usually 10 ft. or more above ground in cavity or hollow tree
Marten <i>Martes americana</i>	Den in hollow tree or log
Fisher <i>Martes pennanti</i>	Den in hollow tree or log
Ermine <i>Mustela erminea</i>	Den in hollow tree or log
Long-tailed weasel <i>Mustela frenata</i>	Den in hollow tree or log
Mink <i>Mustela vison</i>	Den in hollow log, under stump
Striped skunk <i>Mephitis mephitis</i>	Den in hollow log, under stump
Lynx <i>Felis lynx</i>	Den under log overgrown with brush
Bobcat <i>Felis rufus</i>	Den under log overgrown with brush

Cavity Tree Characteristics and Wildlife Values

The preceding section describes how the degree of decay affects wildlife use. Other factors affecting wildlife are a tree's size, location, species or type (deciduous or coniferous), and how it was killed or injured. There are predictable groups of birds and other wildlife that use cavity trees depending on these interacting factors.

A general rule of cavity tree management is that bigger is better. This is so for several reasons. Large birds need large trees in which to excavate nesting and roosting holes—for example, the pileated woodpecker needs at least 20

inches in diameter at breast height (d.b.h.). Also, small birds can find nest sites in large trees, but not vice versa. And a large dead tree or snag will usually stand longer than a small one, and so be available longer. Table 3 is a guide to cavity tree or snag sizes and numbers needed by various woodpeckers for cavity excavation. Emphasis is placed on woodpeckers because habitat management for viable populations of these species will also provide nesting sites for the secondary cavity users.

Location is another factor that determines cavity tree use. Some

species prefer such trees in the open, others within the forest. The flicker is a woodpecker that prefers to nest in open habitat: cavity trees, snags, or stubs at woodland edges, in pastures, or in clearcuts are preferred. Secondary users of flicker cavities are kestrels and eastern bluebirds (*Sialia sialis*), among others. Birds that prefer to excavate nests in more concealed trees are the hairy and pileated woodpeckers and the yellow-bellied sapsucker. Others are intermediate, using open stands or scattered trees: the red-headed (*Melanerpes erythrocephalus*) and red-bellied woodpeckers (*Melanerpes carolinus*) are examples.

Table 3.—Number of cavity trees^a needed to sustain the hypothetical maximum populations of nine species of woodpeckers found in New England

Species	Territory size	Average nest tree ^b		(A) Cavity trees used, minimum	(B) Pairs/100 acres, maximum	Cavity trees needed/100 acres ^c (A X B)
		D.b.h.	Height			
	<i>Acres</i>	<i>Inches</i>	<i>Feet</i>	<i>Number</i>	<i>Number</i>	<i>Number</i>
Red-headed woodpecker	10	20	40	2	10	20
Red-bellied woodpecker	15	18	40	4	6.3	25
Yellow-bellied sapsucker	10	12	30	1	10	10
Downy woodpecker	10	8	20	4	10	40
Hairy woodpecker	20	12	30	4	5	20
Three-toed woodpecker	75	14	30	4	1.3	5
Black-backed woodpecker	75	15	30	4	1.3	5
Northern flicker	40	15	30	2	2.5	5
Pileated woodpecker	175	22	60	4	0.6	2.4

^a After Evans and Conner (1979).

^b Larger trees may be substituted for smaller trees.

^c Number of cavity trees needed to sustain population at hypothetical maximum level.

Cavity trees at the banks of streams or edges of ponds or lakes seem to be preferred by virtually all primary cavity excavators. This may be explained partly by the security provided—perhaps fewer nest predators can approach over water—and partly by the fact that trees near water may be larger and do tend to lean toward the water. Woodpeckers will usually excavate their nest hole on the underside of a leaning tree. Protection of the nest from rain and other elements seems to be the obvious function. Wood ducks (*Aix sponsa*) commonly use old pileated woodpecker holes excavated over water.

In addition to these factors, the extent and pattern of interior decay and the type of tree injury are probably very important factors in cavity trees selected by primary excavators. The ideal nesting substrate for most woodpeckers is a stem or limb (of suitable minimum diameter and height above ground) that is sound on the outside but that contains a central column of decayed wood in which the cavity will be excavated. This condition can result from several causes: decay spreading throughout the tree, decay spreading from a snapped off limb or top, or a compartmentalized area of decay from a wound.

The presence of decay that has been developing for a number of years can usually be detected by spore-bearing structures such as mushrooms or bracket-shaped conks on the trunk. Trees with compartmentalized decay or wounds high on the trunk or in the crown are more difficult to detect. When found, they should be marked for retention because many cavity-nesting birds use live trees.

Dead snags and stubs, while not always common in stands, are usually obvious; they should also be left for wildlife if they are at least 6 inches d.b.h. Snags and stubs that show a history of woodpecker use—new holes excavated sequentially lower as the upper portion breaks away—are especially valuable. Woodpeckers will usually continue to excavate cavities so long as relatively hard or firm outer wood supports a decay column the appropriate height. Finally, only the rotted stub will remain. The hollow formed in the tops of large broken stubs provides a nest site for barred owls (*Strix varia*), hooded (*Lophodytes cucullatus*) and common (*Mergus merganser*) mergansers, and turkey vultures (*Cathartes aura*). Smaller stubs are used by bluebirds and chickadees (Figs. 10 and 11).

Cavity Tree Management

Maintaining existing cavity trees and snags, creating them when absent, and ensuring their continued future availability are wildlife management objectives. Table 3 provides a guide to the number of cavity trees per 100 acres needed to maintain maximum woodpecker population levels. Recall that larger trees can substitute for smaller ones.

On smaller ownerships, one should consider the availability of cavity trees on surrounding forest land. If adjacent lands have few cavity trees, those on a small parcel could be critical to cavity-dependent wildlife.

At each stand entry, maintaining cavity trees, and snags and stubs that are in the proper size classes and diameter should ensure a continuing supply of cavity trees in the condition required by the various wildlife users. These can be trees of inferior form or even noncommercial species. Foresters are able to identify trees with exterior signs of advanced internal decay—presence of fungal conks, and so on. Retention of these trees is the key to ensuring that snags and stubs are present in the future.



Figure 10.—Cavities were excavated in the dead top of this red maple.



Figure 11.—Cavity in black walnut associated with a 25-year-old flush-cut branch.

Generally, both intermediate cuttings (thinning, weeding, etc.) or regeneration cuttings (clearcuts, shelterwood, etc.) eliminate larger cavity trees and snags; these should be clearly marked for retention before any cutting is done. Where broken topped trees occur or result from logging, they should also be saved for wildlife if they do not present a safety hazard.

Natural processes and disturbances such as logging usually produce a sufficient number of cavity trees. However, some stands

have few apparent cavity trees or snags. The usual procedure for the direct creation of snags has been to girdle large trees with a chainsaw, or to cut away a 3- to 4-inch band of bark and cambium around the entire circumference of the trunks with an axe or hatchet, or to inject them with herbicide.

Where no trees exhibit signs of decay, as in a young stand, nest boxes can be used to attract secondary cavity nesters. Boxes should be constructed so that they can be opened for autumn cleaning. Nest

box dimensions are given in Table 4. In the Northeast, nest boxes need not be stained or painted. They should be erected in autumn so that they weather before spring. Boxes can be erected on posts or fastened (aluminum nails) directly to the undersides of slightly leaning trees.

Den trees are living hollow trees that are used as homes by mammals (Fig. 12). Species using den trees vary greatly, ranging from mice (*Peromyscus* spp.) and flying squirrels (*Glaucomys* spp.), to gray squirrels (*Sciurus carolinensis*), rac-

Table 4.—Dimensions of nest boxes and placement heights for secondary cavity-nesting forest birds of New England

Species	Inside walls		Entrance hole		Height above ground	Placement
	Width	Height	Diameter	Height above floor		
	----- Inches -----				Feet	
Eastern bluebird	4.5	8	1-1/2	6	4-8	In fencerow, clearcut
Black-capped chickadee	4	8-10	1-1/8	6-8	6-15	Forest interior
Tufted titmouse	4	8-10	1-1/4	6-8	6-15	Edge of mixed woods
Nuthatches	4	8-10	1-1/4	6-8	12-20	Forest interior
House wren	4	6-8	1	1-6	6-10	Forest edges
Carolina wren	4	6-8	1-1/8	1-6	6-10	Forest edges
Tree swallow	5	6	1-1/2	1-5	10-15	Field and pond edges
Northern flicker ^a	7	16-18	2-1/2	14-16	6-20	Forest edges
Red-headed woodpecker ^a	6	12-15	2	9-12	12-20	Open woods, forest edges
Downy woodpecker ^a	4	8-10	1-1/4	6-8	6-10	Forest
Hairy woodpecker ^a	6	12-15	1-1/2	9-12	12-20	Forest interior
Screech-owl	8	12-15	3	9-12	10-36	Woodlots, forest edges, streamsides
Saw-whet owl	6	10-12	2-1/2	8-10	12-20	Forests, woodlots, swamps
American kestrel	8	12-15	3	9-12	10-36	On large dead tree in pasture, field
Wood duck ^b	12	24	4 x 3 (Horizontal oval)	18-20	10	In pond or wooded swamp

^a Boxes for woodpeckers need be provided only if stands are uniformly polesized or if no cavity trees are present. The species included occasionally use nest boxes.

^b For complete instructions, see USDI, Fish and Wildlife Service (1976).



Figure 12.—A small entrance hole in the center of the closed wound on this birch. A central column of decayed wood is behind the wound.

coons (*Procyon lotor*), and black bears (*Ursus americanus*) (Table 3). In New England, such trees are usually old boundary or "leave" trees, or large lone trees in fence rows or along old roads. Thus, they are not well distributed across the landscape. There are generally fewer than could be used by wildlife. For example, Southern New England contains 4,998,600 acres of commercial forest land (Kingsley 1974). Among large sawtimber hardwoods (15.0 inches and larger), 3.1 percent are rough and rotten trees¹ 21.0 to 28.9 inches d.b.h. Less than 0.5 percent of such trees are greater than 29 inches d.b.h. Together, these size classes contain the existing and potential den trees in Southern New England woodlands.

By area, then, southern New England contains 16.3 rough and rotten trees at least 21.0 inches d.b.h., per 100 acres of commercial forest land (Table 5).

Gray squirrels, for example, can occupy up to 25 or more den trees per 100 acres because their home range is often less than 2 acres (Doebel and McGinnes, 1974).

Cavity trees generally have central columns of decay in the limbs or trunk; den trees are hollow or have large hollow limbs, but are otherwise vigorous. Most den trees have rather conspicuous openings in sound wood—usually either a round hole on the trunk where a dead limb had dropped off or an opening at the base resulting from a

¹ Rotten trees.—Live trees of commercial species that do not contain at least one 12-foot sawlog or two noncontiguous sawlogs, each 8 feet or longer, now or prospectively, and do not meet regional specifications for freedom from defect primarily because of rot; that is, when more than 50 percent of the cull volume in a tree is rotten.

Rough trees.—(a) The same as above, except that rough trees do not meet regional specifications for freedom from defect primarily because of roughness or poor form, and (b) all live trees that are of noncommercial species.

Table 5.—Large sawtimber trees on commercial forest land by diameter class and condition, Southern New England, 1972^a
[In thousands of trees]

Species	Diameter class (inches at breast height)				
	Growing-stock trees			Rough and rotten trees	
	15.0–20.9	21.0–28.9	29+	21.0–28.9	29+
Eastern white pine	7,485	874	86		
Eastern hemlock	1,779	290	20		
Other softwoods	574	—	—		
Total softwoods	9,838	1,164	106	205	138
Select white oaks <i>Quercus alba</i> , <i>Q. bicolor</i>	1,490	195	11		
Select red oaks <i>Quercus rubra</i>	5,879	606	84		
Other white oaks	172	—	—		
Other red oaks	3,508	271	24		
Hickories	570	108	10		
Sugar maple	1,100	247	11		
Soft maples	2,201	216	31		
Beech	436	56	—		
White ash	639	132	—		
Other hardwoods	1,589	241	8		
Total hardwoods	17,584	2,072	179	735	115

^aThere are 4,998,600 acres of commercial forest land in New England.

fire scar or other wound. But some much-used den trees are large hardwoods whose top was snapped off previously. Even though the opening would seem to offer little protection from the elements, such trees are common den sites for raccoons.

Den trees that grow in open areas—at old homesites, along roads or fences—tend to have large wide crowns. They are frequently very valuable for wildlife because they often produce more mast or fruit than trees with smaller, more erect crowns.

Den Tree Management

In most cases, den trees need only be marked for retention. Probably all trees greater than 29 inches d.b.h. should be retained when possible, along with smaller living trees with major defects on the trunks—such as open or spiral seams, butt scars, or holes—retained as replacements. An ideal den tree distribution for wildlife would be two or more very large (> 29 inches d.b.h.) den trees per 100 acres for raccoons, opossums (*Didelphis virginiana*), porcupines (*Erethizon dorsatum*) and the like, and 25 such trees 21 to 28.9 inches

d.b.h. per 100 acres for squirrels and other small mammals that use tree dens. Birds such as owls will use these trees also. Den trees have low stumpage values and then only once. The development of a very large den tree takes a century or more; some species such as red and white oaks and sugar maple can live for several centuries. When it falls, the hollow log can last another quarter-century, and later, the rotted stem is used by terrestrial reptiles and amphibians—for example, the

ringneck snake (*Diadophis punctatus*) and redback salamander (*Plethodon cinereus*)—as breeding habitat. Finally, a barely discernible patch of dust, used by ruffed grouse (*Bonasa umbellus*) and other birds for dusting, is left. The process of den tree development and sequential use by wildlife can last for more than 400 years.

Where no den trees exist, the process can be started by cutting off a 4- to 6-inch limb of a tree 20

inches or more in diameter, leaving a stub about 6 inches from the trunk. Or chop out a section of bark and inner wood 6 x 6 inches at the base of a suitable wolf tree. These open wounds allow fungal diseases to enter the tree and begin processes, which over several years will sometimes form a natural cavity surrounded by sound wood. Ash, beech, hemlock, and basswood are especially good trees to select for a future den tree because they readily form natural cavities.



Wildlife Use of "Sound" Trees

Although the wildlife values of cavity trees and den trees are considerable, it is also necessary to consider wildlife use of sound or apparently sound trees. Yellow-bellied sapsuckers nest in the firm decayed wood of soft hardwoods such as aspen. Often, the column of firm decayed wood is difficult to detect. Other woodpeckers also excavate cavities in trees, usually spruce or fir, that show no outward sign of decay.

Urban Hazard Trees — Wildlife Trees

It is possible to have wildlife trees in parks and other open spaces used by people. Rotted wood that is about to fall is unlikely to be used for nesting or denning and should be cut to prevent injury to people or property damage. However, proper pruning of large dead branches may help preserve a hazard tree for wildlife. The small diameter ends should be removed to reduce strain on the lower, thicker portion of the branch. Cavities will usually be in the thicker portions. Weak branches, dead or alive, can be cabled and braced to prevent breakage. In some situations, planted shrubs, or even a fence could be put around select wildlife trees to keep people away.

A Look to the Future

Will we have enough large trees for wildlife in the future? The trend on much managed forest land is toward smaller trees. We do know that the degree of compartmentalization is under moderate to strong genetic control. It is time to begin selecting trees for our forests and cities that are strong compartmentalizers. A strong compartmentalizing tree will not only provide us with more and better quality products, but also will, if not cut down, stay alive long enough to grow to a large size. Small, weak, unhealthy trees provide people and wildlife with few benefits. Even if cavities form in small unhealthy trees, they will be small and short-lived. The best type of tree for people and wildlife is the strong tree that will grow relatively quickly to a massive size and stand a long time. And, strong compartmentalizing ability will result in strong-boundaried cavities that will last. Tree species and their cavity values are shown in Table 6.

Table 6.—Characteristics of common New England trees that have high cavity values for wildlife

Tree species	Life span	Mature height	Mature d.b.h.	Comments
	<i>Years</i>	<i>Feet</i>	<i>Inches</i>	
E. white pine <i>Pinus strobus</i>	450	80-100	24-42	Trees with snapped-off tops most valuable for cavity excavation.
E. hemlock <i>Tsuga canadensis</i>	400-600	60-70	24-36	
White oak <i>Quercus alba</i>	500-600	50-100	36-48	Excellent shade and den trees.
N. red oak <i>Quercus rubra</i>	200-300	60-100	36	Excellent shade and den trees.
Black oak <i>Quercus velutina</i>	200	60-80	36	Usually loses to competition on good sites; common on dry, sandy sites.
Sugar maple <i>Acer saccharum</i>	200-300	60-100	24-36	Excellent shade tree. Readily forms branch core cavities.
American beech <i>Fagus grandifolia</i>	300-400	70-80	24-36	Valuable for cavity excavation, but dead wood decays rapidly.
White ash <i>Fraxinus americana</i>	100	70-100	24-48	Grows vigorously and readily forms trunk cavities if top broken.



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This paper is a guide for woodland owners, managers, or arborists who want to provide key habitat components for northeastern cavity-nesting birds and mammals that use tree dens. Methods for creating and maintaining cavity trees, snags, and den trees are described.

ODC 151

Keywords: Compartmentalization, discoloration and decay, birds, mammals.

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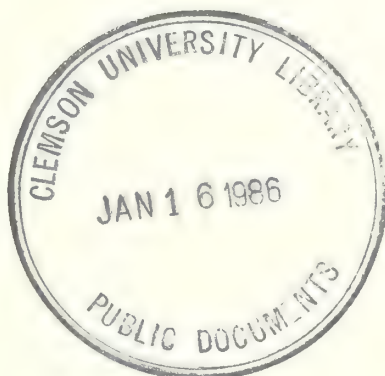
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DESIM Data Manual:

A Procedural Guide for Developing Equipment Processing and Down Time Data

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Abstract

A procedural guide for developing the equipment processing and down time information required by the DESIM computerized system for designing and simulating hardwood sawmills. Instructions are provided for collecting and processing data for the different types of sawmill equipment to assure that the information matches the procedures used in the system. These instructions must be followed to obtain realistic results from the simulator.

DESIM Data Manual: A Procedural Guide for Developing Equipment Processing and Down Time Data

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Introduction

The computerized system DESIM¹ (DEsign SIMulator) is available for designing and simulating the operation of hardwood sawmills. It can be used to: (1) design new mills, (2) modify existing mills, and (3) analyze the operation of existing mills. To aid in the understanding and use of the system, two general technical reports are available—a general discussion and a user's manual (Adams 1984a, b).

The system consists of three computer programs and two support data files. The first program provides data forms for recording the information needed to set up a sawmill system. The second program uses a question-and-answer technique to aid the user in transferring information from the data forms into a computer data file. The third program uses the data file to simulate the operation of the sawmill system. The two support data files consist of: (1) standard machine times and rates for different types of sawmill equipment, and (2) lumber grade yield information (Hanks 1973, Hanks et al. 1980).

To use DESIM, it is necessary to have equipment processing time and down time information for each machine center in the proposed sawmill. Some of this information is already available in the system's equipment data file. However, when the information is not available or if the user is not satisfied with the available information, it must be developed. When developing the information, the procedures presented in this report should be used to assure that the data matches the procedures used in the simulator. This will also standardize the information allowing confident use and trading of the data between users.

¹ The computer programs described in this publication are available on request with the understanding that the U.S. Department of Agriculture cannot assure their accuracy, completeness, reliability, or suitability for any other purpose than that reported. The recipient may not assert any proprietary rights thereto nor represent them to anyone as other than Government-produced computer programs.

Procedure

The procedure for collecting and analyzing equipment processing and down time information will be discussed separately for each type of sawmill equipment. The equipment types are:

- 1—Forklift (raw material handler)
- 2—Crane (raw material handler)
- 3—Bucksaw
- 4—Debarker (Rosserhead-type)
- 5—Debarker (ring-type)
- 6—Headrig (band and circular)
- 7—Headrig (Scragg and gang)
- 8—Edger (standard and combination)
- 9—Resaw (gang, centerline, and line-bar)
- 10—Special product station
- 11—Trimsaws
- 12—Green chain
- 13—Chipper
- 14—Transfer station

The procedure given for each equipment type should be followed closely. When collecting the data, be sure to record all times in minutes and hundredths of a minute and record all piece lengths in feet and tenths of a foot. Record log and bolt diameters as indicated in the instructions.

In these procedures, most of the resulting values fall into one of two categories—a mean value or a set of lognormal parameters. The mean value is simply an arithmetic average of a set of data. The lognormal parameters for a set of data consists of a mean, minimum value, maximum value, and standard deviation of the logarithms of the individual data values. Appendix A provides: (1) a discussion of the parameters, (2) instructions for obtaining a computer program for calculating them, and (3) instructions for using the program. In the following procedures when lognormal parameters are to be calculated, use the method and computer program shown in this Appendix.

As in any study, sample size is important when developing the processing and down time information required for the various pieces of equipment. Whether collecting data for a mean value or for lognormal parameters, I recommend taking at least 30 observations (based on the central-limit theorem).

For each piece of equipment, DESIM allows processing and down time information to be entered separately for 12 different species. The species codes are:

- 1—Northern red oak
- 2—Black oak
- 3—Scarlet oak
- 4—White oak
- 5—Chestnut oak
- 6—Sugar maple
- 7—Red maple
- 8—Yellow-poplar
- 9—Basswood
- 10—Black cherry
- 11—Yellow birch
- 12—Beech

However, if species does not significantly affect the processing and down times, the information can be entered with a species code of 13. This indicates that the information is for all species combined.

After developing the processing and down time information for a given piece of equipment, it either can be used directly as input to the DESIM system or can be entered into the DESIM equipment data file. Appendix B shows an example from the equipment data file and discusses the procedure for changing existing information or entering new information.

1. Forklift (Raw Material Handler)

This is a forklift for loading raw material onto a log or bolt deck at the input end of a mill. The information needed for this machine is:

Species XX

Processing time (minutes) XXX.XX

Processing time distribution:

Lognormal Distribution

		Mean	Minimum	Maximum	SD
Down time	. . . .	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Percent down	. . . .	XX.XXX			

1.1 Processing time (minutes). This is the average time per piece required to load raw material onto a log or bolt deck. In collecting the data, record the round-trip time required by the forklift to travel from the deck to storage, return with a load of material, and place the material onto the deck. Also, record the number of pieces in the load. Repeat this procedure at least 30 times. Next, sum both the times and the number of pieces. Then, calculate the required average processing time by dividing the total time by the total number of pieces.

1.2 Down time (lognormal parameters and percent down). The instructions in this section not only apply to the forklift, but also apply to all other pieces of equipment. The nonscheduled down time information consists of two parts: a “percent down” and parameters for a lognormal frequency distribution. The “percent down” represents the frequency that the machine can be expected to go down. The parameters represent the lognormal frequency distribution of the lengths of time the machine can be expected to be down once it goes down. To collect the down time data, tally the number of pieces processed (N_p) by the machine during the study period. Also, tally the number of times (N_d) that a piece is available but cannot be processed (that is, machine is down). Each time the machine is down, record the length of the down time. A machine should be considered down only when the inability to process a piece of material is due to problems directly related to the machine or its operator. This includes problems with the machine’s buffer or conveyor systems. Do not consider the machine down when: (1) scheduled down times occur, (2) material is not available, or (3) the machine is blocked down stream due to the production rates of other machines or other machines being down. The down time study should cover at least 1 full workday. A full workweek would be much better. The lognormal parameters for the down time frequency distribution should be based on no less than 30 observations.

Down time (lognormal parameters)—These parameters include a mean, minimum value, maximum value, and standard deviation for a lognormal frequency distribution of the down times collected during the above study. Use the procedure and computer program in Appendix A to calculate the parameters.

Percent down—To determine the required “percent down,” divide the down count (N_d) by the processing count (N_p) from the above study. For example, if during the study period a machine went down 50 times while processing 1,000 pieces, the “percent down” would be 5.0 percent.

2. Crane (Raw Material Handler)

This is a crane or knuckle-boom loader for loading raw material onto a deck or conveyor at the input end of a mill. The information needed for this machine is:

Species XX

Processing time (minutes) XXX.XX

Processing time distribution:

Lognormal Distribution

		Mean	Minimum	Maximum	SD
Down time	. . . .	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Percent down	. . . .	XX.XXX			

2.1 Processing time (minutes). This is the average time it takes to load a piece of raw material onto a deck or conveyor. To obtain the data, record the round-trip time required to reach for, pick up, and place material onto the deck or conveyor, and tally the number of pieces for the trip. Repeat this procedure at least 30 times. Next, sum both the times and the number of pieces. Then determine the required average processing time by dividing the total time by the total number of pieces.

2.2 Down time (lognormal parameters and percent down). See instructions in Section 1.2 for collecting and processing the data for this required information.

3. Bucksaw This is a saw for bucking long-length logs into standard sawlogs and/or bolts. The information needed for this machine is:

Species XX

Feed rate (inches/minute) XXX.XX

Processing time distributions:

Lognormal Distributions

		Mean	Minimum	Maximum	SD
Load time	. . . .	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Down time	. . . .	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Percent down	. . . .	XX.XXX			

3.1 Feed rate (inches/minutes). This is the average feed rate of the saw used to buck long-length pieces into logs or bolts. To obtain the data, record the time required for the saw to make the buck cut. Also record the diameter (to the nearest inch) of the piece at the buck cut. Repeat this procedure at least 30 times over the range of diameters usually bucked. For each buck cut, divide the diameter by the time to get the individual feed rates. To obtain the required average feed rate, sum the individual feed rates and divide by the number of buck cuts in the sample.

3.2 Load time (lognormal parameters). These parameters represent a lognormal frequency distribution of the times required to position a long-length piece to be bucked into logs and/or bolts. To obtain the necessary data, record the time between the finish of one buck cut and the start of the next. Repeat this procedure at least 30 times. Make sure that a proportionate number of these times includes the time between the last cut or one long-length piece and the first cut on the next. For example, if 10 long-length pieces are processed during the collection of the 30 load times, at least 10 of these times should represent the time between the last cut on one long-length piece and the first cut on the next. Use this time data to determine the required load-time lognormal parameters.

3.3 *Down time (lognormal parameters and percent down)*. See instructions in Section 1.2 for collecting and processing the data for this required information.

4. Debarker (Rosserhead-Type)

The following information is needed for Rosserhead-type debarkers:

Species XX

Processing time (minutes/10 ft²) XXX.XX

Processing time distributions:

Lognormal Distributions

		Mean	Minimum	Maximum	SD
Load time	. . . .	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Down time	. . . .	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Percent down	. . . .	XX.XXX			

4.1 *Processing time (minutes/10 ft²)*. This is the average processing time (in minutes per 10 ft² of surface area) required to debark logs and/or bolts on a Rosserhead-type debarker. This processing time is scaled by a factor of 10 to eliminate a decimal place when entering the value into the DESIM system. The time required to load the piece is not included in this time. To obtain the necessary data for each study piece, time the period from the start of debarking (that is, when the debarker head hits the piece) until the piece leaves the debarker. For the piece also record both end diameters (in feet and tenths of a foot) and the length. Repeat this procedure for at least 30 pieces over the range of sizes usually processed. Once the data have been collected, use the following procedure: For a study piece, average the two end diameters and use the resulting average diameter to determine the average circumference. Multiply this circumference by the piece length to obtain an estimate of the surface area in square feet. Divide the processing time by the estimated surface area and multiply by 10 to obtain the processing time in minutes per 10 ft² of surface area. Repeat this procedure for each piece. Finally, sum these individual processing times and divide by the number of study pieces to obtain the required average processing time in minutes per 10 ft² of surface area.

4.2 *Load time (lognormal parameters)*. These parameters represent a lognormal frequency distribution of the times required to load a log or bolt onto the debarker. To obtain the necessary data, record the time between one piece leaving the debarker and the next piece hitting the debarker head. Repeat this procedure for at least 30 pieces. Use these recorded times to determine the required load-time lognormal parameters.

4.3 *Down time (lognormal parameters and percent down)*. See instructions in Section 1.2 for collecting and processing the data for this required information.

5. Debarker (Ring-Type) The following information is needed for ring-type debarkers:

Species. . . .XX

Feed rate (feet/minute). . . .XXX.XX

Processing time distributions:

Lognormal Distributions				
	Mean	Minimum	Maximum	SD
Load time	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Down time	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Percent down	XX.XXX			

5.1 Feed rate (feet/minute). This is the average feed rate (in feet per minute) for pieces being fed through a ring-type debarker. To obtain the necessary data, record the time that it takes to debark the piece. This time must not include the time to position or load the piece. Also, record the piece length. Repeat this procedure for at least 30 pieces. Once the data have been collected, divide the debarking time by the piece length to get the individual feed rate for each study piece. Then sum these individual feed rates and divide by the number of study pieces to obtain the required average feed rate.

5.2 Load time (lognormal parameters). See instructions in Section 4.2 for collecting and processing the data for this required information.

5.3 Down time (lognormal parameters and percent down). See instructions in Section 1.2 for collecting and processing the data for this required information.

6. Headrig (Circular and Band)

The DESIM system can handle both circular and band headrigs. It can also handle these headrigs with or without a vertical edger. And the DESIM equipment data file will accept data for all four situations. The following information is needed for each of these headrig situations:

Species. . . .XX

Processing time distributions:

Lognormal Distributions				
	Mean	Minimum	Maximum	SD
Load time	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Turn time	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Slab time	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Line time	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Down time	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Percent down	XX.XXX			

6.1 Load time (lognormal parameters). These parameters represent a lognormal frequency distribution of the time required to load logs and/or bolts onto a headrig carriage. In collecting the data, start timing a loading sequence when the carriage stops after returning from the last cut on a previous log or bolt. Stop the time as soon as the piece has been loaded and dogged for the first pass at the saw. Record the elapse time. Repeat this procedure for at least 30 loading sequences. Use these recorded times for determining the required lognormal parameters.

6.2 Turn time (lognormal parameters). These parameters represent a lognormal frequency distribution of the times required to turn a log or bolt on a headrig carriage. In collecting the data, start timing the turn sequence when the carriage stops after returning from sawing a line or making a slab cut. Stop the time as soon as the piece has been turned and dogged for the next pass at the saw. Record the elapse time. Repeat this procedure for at least 30 turning sequences. Use these recorded times for determining the required lognormal parameters.

6.3 Slab time (lognormal parameters). These parameters represent a lognormal frequency distribution of the processing rates (in minutes per 10-foot log length) for sawing slabs from logs or bolts. In collecting the data, start timing the slab sequence as soon as the piece has been dogged for a pass at the saw. Stop the time as soon as the carriage returns from the slab cut and stops. Record the elapse time and the length of the piece from which the slab was cut. Repeat this procedure for at least 30 slabbing sequences for pieces representing the range of diameters and lengths usually processed. Once the data have been collected, use the following procedure: For a slab cut, divide the time by the length of the piece and multiply the result by 10. This multiplication by 10 is used to scale the data for calculation purposes. Repeat this procedure for each slabbing sequence. The resulting times per 10-foot log length are used for determining the required lognormal parameters.

6.4 Line time (lognormal parameters). These parameters represent a lognormal frequency distribution of the processing rates (in minutes per 10-foot log length) required to saw a line. In collecting the data, start timing the line sequence as soon as the piece has been dogged for a pass at the saw. Stop the time as soon as the carriage returns from the cut and stops. Record the elapse time and the length of the piece on which the cut was made. Repeat this procedure for at least 30 line sequences from pieces representing the range of lengths and diameters usually processed. Once the data have been collected, use the following procedure: For a line cut, divide the time by the piece length and multiply the result by 10. This multiplication by 10 is used to scale the data for calculation purposes. Repeat this procedure for each line sequence. The resulting times per 10-foot log length are used for determining the required lognormal parameters.

6.5 *Down time (lognormal parameters and percent down).* See instructions in Section 1.2 for collecting and processing the data for this required information.

7. Headrig (Scragg and Gang)

The DESIM system can also handle both Scragg and gang headrigs. And the DESIM equipment data file will accept data for both. The following information is needed for each of these headrigs:

Species. . . .XX

Feed rate (feet/minute). . . .XXX.XX

Processing time distributions:

		Lognormal Distributions			
		Mean	Minimum	Maximum	SD
Load time	....	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Down time	....	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Percent down	....	XX.XXX			

7.1 Feed rate (feet/minute). This is the average feed rate (in feet per minute) for pieces being fed through the machine. To obtain the necessary data, record the time that it takes for the piece to pass through the saws. The time starts when the piece hits the saws and stops when it leaves the saws. This time must not include the time to position or load the piece. Also record the piece length. Repeat this procedure for at least 30 pieces. Once the data have been collected, divide the sawing time by the piece length to get the individual feed rate for each piece. Then sum these individual feed rates and divide by the number of pieces to obtain the required average feed rate.

7.2 Load time (lognormal parameters). These parameters represent the lognormal frequency distribution of the times required to load and/or position a log or bolt to be processed by the machine. To obtain the necessary data, record the time interval from the time the previous piece leaves the saws until the next piece hits the saws. Repeat this procedure for at least 30 pieces. Use these recorded times to calculate the required load-time lognormal parameters.

7.3 Down time (lognormal parameters and percent down). See instructions in Section 1.2 for collecting and processing the data for this required information.

8. Edgers (Standard and Combination)

The DESIM system can handle both standard and combination edgers. A standard edger has movable saws for edging boards only. A combination edger has movable saws for edging boards on one side and a set of saws for gang sawing cants on the other. The following procedure is for a combination edger. If this procedure is to be used for a standard edger, just eliminate the parts for determining the "cant feed rate" and the "cant load time (lognormal parameters)." The DESIM equipment data file will accept data for both edger types. The following information is needed:

Species. . . .XX

Feed rate (feet/minute):

Board
XXX.XX

Cant
XXX.XX

Processing time distributions:

Lognormal Distributions

	Mean	Minimum	Maximum	SD
Board load time	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Cant load time	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Down time	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Percent down	XX.XXX			

8.1 Board or cant feed rate (feet/minute). Use this procedure to determine the feed rate for both boards and cants. This is the average feed rate in feet per minute for pieces being processed by the edger. To obtain the necessary data, record the time that it takes for the piece to pass through the saws. The time starts when the piece hits the saws and stops when it leaves the saws. This time must not include the time to position or load the piece. Piece length is also recorded. Repeat this procedure for at least 30 pieces. Once the data have been collected, divide the sawing time by the piece length to get the individual feed rates. Then sum these individual feed rates and divide by the number of pieces to obtain the required average feed rate.

8.2 Board or cant load time (lognormal parameters). Use this procedure to determine the load time for both boards and cants. These parameters represent the lognormal frequency distribution of the times required to load and/or position the piece to be processed through the edger. To obtain the necessary data, record the time between one piece leaving the saws and the next piece hitting the saws. Repeat this procedure for at least 30 pieces. Use these recorded times to determine the required load-time lognormal parameters.

8.3 Down time (lognormal parameters and percent down). See instructions in Section 1.2 for collecting and processing the data for this required information.

9. Resaw (Gang, Centerline, and Line-Bar)

The DESIM system can handle gang, centerline, and line-bar type resaws. And the DESIM equipment data file will accept data for all three types. The following information is needed for each:

Species. . . .XX
 Feed rate (feet/minute). . . .XXX.XX
 Processing time distributions:

Lognormal Distributions

		Mean	Minimum	Maximum	SD
Load time	....	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Down time	....	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Percent down	....	XX.XXX			

9.1 Feed rate (feet/minute). See instructions in Section 7.1 for collecting and processing the data for the required information.

9.2 Load time (lognormal parameters). See instructions in Section 7.2 for collecting and processing the data for the required information.

9.3 Down time (lognormal parameters and percent down). See instructions in Section 1.2 for collecting and processing the data for the required information.

10. Special Product Station

This machine center processes boards or cants by cutting them into shorter pieces; for example, the production of coal mine headers and half headers. The following information is needed:

Species. . . .XX
 Processing time (minutes). . . .XXX.XX
 Processing time distribution:

Lognormal Distribution

		Mean	Minimum	Maximum	SD
Down time	....	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Percent down	....	XX.XXX			

10.1 Processing time (minutes). This is the average processing time (in minutes per piece) required to produce a short piece from a board or cant. To obtain the data, count the number of short pieces produced during a given period (for example, 1 hour). If any down, idle, or blocked times occur during the time period, subtract these times from the study time period. Record the resulting time and the number of pieces produced. Then to obtain the required average processing time, divide the recorded time by the number of pieces produced.

10.2 Down time (lognormal parameters and percent down). See instructions in Section 1.2 for collecting and processing the data for this required information.

- 11. Trimsaws** This machine center has two or more saws for trimming boards and cants to specific lengths. The information needed for this machine is:

Species. . . .XX

Processing time (minutes). . . .XXX.XX

Processing time distribution:

		Lognormal Distribution			
		Mean	Minimum	Maximum	SD
Down time	....	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Percent down	....	XX.XXX			

11.1 Processing time (minutes). This is the average processing time (in minutes per piece) required to trim a piece. To obtain the data, count the number of pieces trimmed during a given period of time (for example, 1 hour). If any down, idle, or blocked times occur during the time period, subtract these times from the study time period. Record the resulting time and number of pieces trimmed. Then to obtain the required average processing time, divide the recorded time by the number of pieces trimmed.

11.2 Down time (lognormal parameters and percent down). See instructions in Section 1.2 for collecting and processing the data for this required information.

- 12. Green Chain** Although the green chain is not a machine center, it is treated as one by DESIM. The information needed for the green chain is:

Species. . . .XX

Processing time (minutes). . . .XXX.XX

Processing time distribution:

		Lognormal Distribution			
		Mean	Minimum	Maximum	SD
Down time	....	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Percent down	....	XX.XXX			

12.1 Processing time (minutes). This is the average processing time (in minutes per piece) required to pull both boards and cants from the green chain and stack them. To obtain the data, count the number of pieces pulled and stacked during a given time period (for example, 1 hour). If any down, idle, or blocked times occur during the time period, subtract these times from the study time period. Record the resulting time and the number of pieces processed. Then to obtain the required average processing time, divide the recorded time by the number of pieces processed.

12.2 Down time (lognormal parameters and percent down). See instructions in Section 1.2 for collecting and processing the data for this required information.

13. Chipper The following information is needed for the chipper:

Species. . . .XX

Feed rate (feet/minute). . . .XXX.XX

Processing time distribution:

Lognormal Distribution

		Mean	Minimum	Maximum	SD
Down time	....	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Percent down	...XX.XXX				

13.1 Feed rate (feet/minute). This is the average feed rate (in feet per minute) for slabs processed by the chipper. To obtain the necessary data, record the piece length and the time required to actually chip the piece. Repeat this procedure for at least 30 slabs. Once the data have been collected, divide the chipping time by the slab length to get the individual feed rate for each slab. Then sum these individual feed rates and divide by the number of slabs to obtain the required average feed rate.

13.2 Down time (lognormal parameters and percent down). See instructions in Section 1.2 for collecting and processing the data for this required information.

14. Transfer Station This is a station for transferring material from one conveyor system to another conveyor system. DESIM treats these stations as machine centers. The information needed for a transfer station is:

Species. . . .XX

Processing time (minutes). . . .XXX.XX

Processing time distribution:

Lognormal Distribution

		Mean	Minimum	Maximum	SD
Down time	....	XX.XXX	XX.XXX	XX.XXX	XX.XXX
Percent down	...XX.XXX				

14.1 Processing time (minutes). This is the average time required to pass material through the station. To obtain the data, record the time required to transfer the piece from a conveyor or buffer to another conveyor. Repeat this procedure for at least 30 pieces. Then to obtain the required average processing time, sum the individual times and divide by the number of pieces.

14.2 Down time (lognormal parameters and percent down). See instructions in Section 1.2 for collecting and processing the data for this required information.

Literature Cited

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Appendix A—Lognormal Parameters

Discussion of Lognormal Parameters

Much of the processing and down time information required by the DESIM system comes from data having frequency distributions that are skewed to the right. Because these distributions are difficult to use in the simulation process, the data are transformed by taking the natural log of the individual values. These transformed data have frequency distributions that are normally distributed (lognormal frequency distributions) making them much easier to use. For each of the lognormal frequency distributions, DESIM requires a mean, minimum value, maximum value, and standard deviation. The DESIM User's Manual (Adams 1984b) shows a hand calculator method for developing these parameters. However, I suggest using the computer program discussed here. Not only will the program make the task easier, but it will also reduce the chance of error and provide additional information on how well the lognormal frequency distribution fits the data.

Obtaining Lognormal Computer Program

This computer program is a shortened version of the MLESD program (Schreuder et al. 1978). This program and a sample data set have been added to the 9-track DESIM computer tape discussed in the DESIM User's Manual (Adams 1984b). To obtain the program, move it from the sixth location on the DESIM tape to your conversational monitor system (CMS) file with the designation "LONO FORTRAN A1". To obtain the sample data set, move it from the seventh location to your CMS file with the designation "TIME DATA A1". If you are using an IBM² computer system, this can be done by creating a file designated "GET CNTL A1" and inputting the following statements:

```
//BVVVV JOB          WWWWW, XXXXXXXX

/*PRIORITY           STANDARD

/*LONGKEY            YYYYYYYY

/*ROUTE PRINT        VM1.ZZZZZZZ

//STEP1 EXEC         PGM = IEBGENER

//SYSPRINT DD        SYSOUT = A

//SYSUT1 DD          DISP = (OLD,KEEP)

//                   VOL = SER = DESIM1,

//                   UNIT = TAPE,
```

²The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable.

```
//                                DCB = (RECFM = FB,LRECL = 80,BLKSIZE =
                                6000,DEN = 3)

//                                LABEL = (6,NL)

//SYSUT2 DD                      SYSOUT = B

//SYSIN DD                       DUMMY

//
```

In the first statement "VVVV" is to be replaced with your user's box number, "WWWWW" is to be replaced with your user's account number, and "XXXXXXX" is to be replaced with your name. In the LONGKEY statement, "YYYYYYY" is to be replaced with your password. In the ROUTE PRINT statement, "ZZZZZZZ" is to be replaced with your CMS user's identification (ID) name. Once these statements have been input to "GET CNTL A1", save the file.

To get the computer program, submit the "GET CNTL A1" file from the CMS terminal to the multiple virtual storage (MVS) operating system of the main-frame computer. As soon as the run has been completed, the program will be returned to your CMS reader file. Move the program to your CMS file by reading it from the reader file with the designation "LONO FORTRAN A1".

To get the sample data set, modify the "GET CNTL A1" file by changing "LABEL = (6,NL)" to "LABEL = (7,NL)". Submit "GET CNTL A1" to the MVS operating system. The sample data set will be returned to the reader file. Then move the data set to your CMS file with the designation "TIME DATA A1".

Using Lognormal Computer Program

To run the program (LONO FORTRAN A1) on your CMS system, create an EXEC file (LONO EXEC A1). This file must contain the statements required to control the execution of the program. First enter the statements necessary to erase the output file (LONO OUT A1) if it exists. Next make assignments for the input-output unit numbers used in the program. These assignments by unit numbers are:

- 05—"TIME DATA A1" file output (disk)
- 06—"LONO OUT A1" file input (disk)

Finally enter the statements necessary to load and run the program. If you are using an IBM system, the following EXEC file (LONO EXEC A1) will accomplish these tasks:

```
FORTGI LONO  
  
EXSERV STATE LONO OUT A1  
  
&IF &RETCODE NE 0 &GOTO -LABL  
  
ERASE LONO OUT A1  
  
-LABL  
  
FI 05 DISK TIME DATA A1 (RECFM F LRECL 80 BLKSIZE 80)  
  
FI 06 DISK LONO OUT A1 (RECFM F LRECL 130 BLKSIZE 130)  
  
GLOBAL TXTLIB FORTXLIB  
  
LOAD LOGNORM (CLEAR  
  
START  
  
ERASE LONO LISTING A1  
  
ERASE LONO TEXT A1
```

With these statements entered and the "LONO EXEC A1" file saved, you are ready to run the program. This is done by entering "LONO" at the terminal keyboard.

As soon as the program has run, you will have a new file (LONO OUT A1) in your CMS file. This will be the program output that can be sent to the terminal screen and/or to a printer. To assure that the program is running properly on your system, compare this output with the output shown in Figure 1. At this point, if you want to save the data in the "TIME DATA A1" file and/or the output in the "LONO OUT A1" file, you must rename them. This is necessary after each run.

Once you are assured that the program is working properly, you are ready to determine the lognormal parameters for a set of your own data. First, if you have a file named "TIME DATA A1" in your CMS file, erase or rename it. Next create a new "TIME DATA A1" file and input the following information. The first line must have a data name of no more than 40 characters. The second line must have the double precision format under which the data will be entered. For example, (D5.2) indicates that the data will be entered as XX.XX in columns 1 through 5. Finally, the data are entered one value per line using this format. Once all of the data have been entered and the file saved, you are ready to run the program to obtain the required lognormal parameters.

HEADRIG DOWN TIME (T)

*** RAW DATA STATISTICS ***

OBS.MIN.X = 0.2300 MEAN = 1.9454
OBS.MAX.X = 11.8900 VAR. = 5.4793
NO. OF OBS. = 79. ST. DEV. = 2.3408
INDEX OF SKEWNESS = 2.1986
INDEX OF KURTOSIS = 7.8006
SKEWNESS SQUARED = 4.8338

*** LOGNORMAL DISTRIBUTION ***

MEAN = -0.29800
VARIANCE = 1.94120
STANDARD DEVIATION = 1.39327

*** OBSERVED VS. PREDICTED ***

X1	X2	OBSERVED FREQUENCY	PREDICTED FREQUENCY	RESIDUAL FREQUENCY
0.218-	1.384	51.000	49.539	1.461
1.384-	2.550	7.000	13.215	-6.215
2.550-	3.716	9.000	5.744	3.256
3.716-	4.882	3.000	3.110	-0.110
4.882-	6.048	3.000	1.899	1.101
6.048-	7.214	2.000	1.252	0.748
7.214-	8.380	0.0	0.872	-0.872
8.380-	9.546	3.000	0.633	2.367
9.546-	10.712	0.0	0.474	-0.474
10.712-	11.878	0.0	0.364	-0.364
11.878-	13.044	1.000	0.286	0.714

*** STATISTICAL TEST ***

	(CALC. VALUE)	(SIGNIFICANCE LEVEL)		
		(.01)	(.05)	(.10)
KOLMOGOROV-SMIRNOV	0.0602	0.183	0.153	0.137

* HEADRIG DOWN TIME (T) *
* (DESIM) LOGNORMAL PARAMETERS *
* MEAN MIN. MAX. SD *
* -0.298 -4.465 2.457 1.393 *

Figure 1.—Example of program output for lognormal frequency distribution.

As mentioned earlier, Figure 1 shows an example of the output from a computer run. A great deal of information is shown in this output. The first section shows statistics for the raw or untransformed data. This information is self-explanatory. However, notice that it does indicate that the sample data were skewed to the right. The second section shows the mean, variance, and standard deviation for the transformed data. The third section shows a comparison between the lognormal frequency distribution of the transformed data and the resulting theoretical lognormal frequency distribution. This indicates how well the theoretical distribution fits the actual. The fourth section provides the calculated Kolmogorov-Smirnov value and the critical table values for three different significance levels. This provides the information for a goodness of fit test. If the calculated value is larger than the critical value for the chosen significance level, the lognormal frequency distribution does not fit the data. However, for the processing and down time information required by DESIM, this should not be a problem. Finally, boxed in at the bottom of the output are the required DESIM lognormal parameters.

Appendix B—Equipment Data File

Once the required processing and down time information has been developed for a given piece of equipment, it can be either punched in as input during the design phase of the DESIM run or it can be entered into the equipment data file (EQ DATA A1). This section discusses the procedure for entering the information into the equipment data file.

To illustrate this procedure, assume that the required data have been collected and processed for a circular saw headrig (with vertical edger). The resulting processing and down time information for northern red oak is:

Species. . . 1

Processing time distributions:

Lognormal Distributions

	Mean	Minimum	Maximum	SD
Load time. . .	- 2.281	- 5.116	- 0.587	0.866
Turn time. . .	- 2.763	- 5.404	- 0.704	0.712
Slab time. . .	- 3.135	- 5.521	- 0.983	0.667
Line time. . .	- 3.463	- 5.521	- 1.496	0.788
Down time. . .	- 0.298	- 4.465	2.457	1.393
Percent down. . .	2.000			

To get this information in the equipment data file, you must first get the "EQ DATA A1" file into the EDIT mode on the CMS terminal. Then search down the file until the data for the circular saw headrig (with vertical edger) are found. Figure 2 shows what you can expect to see. The 8's in the left column represent the machine code used by the DESIM system for this headrig. The numbers 1 through 13 heading up the 13 groups of data represent the species codes. As you can see, for species code 1 (northern red oak) the data values are all zero's.

```

8      1 CIRCULAR SAW HEADRIG (W/VERTICAL EDGER)
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      00.000

8      2
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      00.000

8      3
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      00.000

      .
      .
      .

8     13
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      00.000

```

Figure 2.—Equipment data file (EQ DATA A1) information for circular saw headrig (with vertical edger) before entering new information.

Now with the "EQ DATA A1" file in the EDIT mode, the new processing and down time information can be entered. It is only necessary to replace the zero values with the corresponding data keeping the decimal points in their existing locations. Once this has been done, this part of the "EQ DATA A1" file will appear as shown in Figure 3. To complete the procedure, it is only necessary to save the file. Using this procedure, the processing and down time information for any machine can be entered or changed.

```

8      1 CIRCULAR SAW HEADRIG (W/VERTICAL EDGER)
      -2.281 -5.116 -0.587  0.866
      -2.763 -5.404 -0.704  0.712
      -3.135 -5.521 -0.983  0.667
      -3.463 -5.521 -1.496  0.788
      -0.298 -4.465  2.457  1.393
      2.000

8      2
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      00.000

8      3
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      00.000

      .
      .
      .

8     13
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      0.000  0.000  0.000  0.000
      00.000

```

Figure 3.—Equipment data file (EQ DATA A1) information for circular saw headrig (with vertical edger) after entering new information.

Adams, Edward L. **DESIM data manual: a procedural guide for developing equipment processing and down time data.** Gen. Tech. Rep. NE-102. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1985. 23 p.

A procedural guide for developing the equipment processing and down time information required by the DESIM computerized system for designing and simulating hardwood sawmills. Instructions are provided for collecting and processing the data for the different types of sawmill equipment that can be considered when using the system.

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